THE DEVELOPMENT OF VISUAL PERCEPTION OF NUMEROSITY IN INFANCY

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THE DEVELOPMENT OF VISUAL PERCEPTION OF NUMEROSITY IN INFANCY

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Erik van Loosbroek

Contents

1 General Introduction

We analysed the evidence on numerosity perception in infancy and the questions that remained concerning the nature of this ability and its development. In addition, we analysed two areas of research that we assumed to be related to numerosity perception. The first area is the development of object perception in infancy. The second area is the development of number knowledge after infancy. The implications of both areas for the study of numerosity perception were discussed The chapter ends with a brief overview of the rest of the thesis

Introduction

Objects play an important role in the visual world of an infant. They are unitary, bounded, and persisting elements. Objects occur sometimes as single elements and sometimes in collections. As unitary, bounded elements, objects can be counted. Do infants perceive the numerosity of collections of objects? Do infants also perceive changes in the numerical size of a collection of objects? How does numerosity perception develop? These questions form the basis of the present thesis.

Evidence that infants are able to perceive numerosity was already provided some years ago by Starkey and Cooper (1980) and by Strauss and Curtis (1981). In general, they showed that infants from at least 4 months of age perceive the numerosity of small collections of elements. Infants were habituated to static displays from 1 to 4 elements. Although they were not solid objects, these pictorial elements essentially were displayed as objects. After habituation, infants were presented with novel collections in the test phase that could be either smaller or greater in numerical size than the ones seen previously. Typically, collections of the same numerosity varied in density, configuration, color or contour of the elements. Therefore, increases in looking time from habituation to test phase must be attributed to the change in numerosity and not to changes in non numerical properties such as density.

Although these studies provided clear evidence that infants can perceive the numerical size of small collections of objects, the studies were less clear about the nature of this ability and how it develops. Hypotheses about the nature of numerosity perception and its development stem from two broad areas of research. The first area is the development of object perception in infancy. The second area is the development of number knowledge after infancy. Both areas have implications for the study of numerosity perception, and sometimes these implications are related. For the sake of clarity, however, we will discuss the implications of both areas for numerosity perception separately in two subsequent sections. In the final section, we will specify the hypotheses that we investigated in a series of studies that will be presented in this thesis.

The development of object perception

When infants are able to perceive the numerosity of collections of objects, we assume that infants, at least, are able to perceive the objects involved. They have to perceive objects as persistent and bounded entities even if objects are partly occluded by other objects, or completely occluded by a screen.

Many studies have been undertaken to systematically assess whether infants perceive objects as persistent, bounded units, and under which constraints they are able to do this (for overviews see Baillargeon, 1993; Bower, 1979; Spelke, 1990). Taken together, these studies gave converging evidence that infants at the age of about 5 months may pick up information that specifies objects as unitary, bounded, and persistent across spatio-temporal variations.

The numerous studies by Spelke and her colleagues using a variety of methods have provided a detailed and impressive account of the extent that infants perceive the unity of objects on the basis of their motions, arrangement, surfaces and forms. For example, Kellman and Spelke (1983) investigated infants' perception of partly occluded objects and the basis for perceiving the unity of those objects. They showed that perception of the unity of a moving object is not affected by the similarity of its visible surfaces in color and texture, the alignment of its edges, or the simplicity of its overall shape. In other words, infants initially appear to perceive partly occluded objects by obtaining information about the motions of their visible surfaces but not by analysing the colors or forms of these surfaces. In addition, Spelke, von Hofsten, and Kestenbaum (1989) found that separated and separately moving objects were perceived as distinct elements.

The studies by Baillargeon focused on infants' perception of enduring object properties when objects moved out of sight behind a screen. The studies had to establish whether infants perceive the objects that go out of sight as persisting units. It was found that 5-month-old infants perceive an object as a persisting and distinct unit when this object is occluded by a backwards rotating screen (Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985). Infants appeared to be surprised when the occluding screen rotated backwards and was occupying the space that should already be occupied by the solid object that had been placed there visibly before the rotation started.

To a large extent, the above findings about perception of objects can also be applied to perception of pictorial elements. If these elements are static, perception of such elements as unitary is dependent on their spatial separation and not on how they are shaped, or patterned. When elements are clearly separated, they are perceived as distinct. On the other hand, when pictorial elements are depicted as one behind another, perception of their distinctness becomes different and is acquired much later than for solid objects (see Yonas & Granrud, 1984).

Although it has become increasingly clear that infants can detect the unity and boundedness of objects, it still is not generally agreed upon what type of processes can account for infants' accomplishments, let alone how these processes develop. Various hypotheses have been proposed to account for these findings. They roughly can be divided into two categories: hypotheses that consider cognitive, reasoning or thinking processes, on the one hand, and hypotheses that consider only perceptual processes, on the other hand. Spelke (1988, 1994) and Baillargeon (1993) both conceive object perception as guided by concepts of objects that an infant is innately equipped with. With development, these concepts become more differentiated through progressive elaboration of details. In Spelke's view, the only role of perception is detection of the arrangement and motion of surfaces.

The ecological perspective (e.g., E.J. Gibson, 1988; J.J. Gibson, 1979) offers a broader view on perception. Within this perspective, one conceives object perception as guided by information that specifies the unity and persistence of objects. This information becomes especially available when objects undergo transformations such as continuous displacement. Changes such as object motion produce a spatio-temporal array composed of variant and invariant structure. The variant structure specifies the object's motion. The invariant structure specifies the object as discrete, bounded, solid and persistent even when the object is displaced or temporarily occluded behind a screen. Perception of an object is then based on obtaining the information specifying the unity and boundedness of objects. Through a process of differentiation, the development of perception would include progressively greater sensitivity to diverse information about unity. For example, infants would also come to obtain unity information of occluding objects that, for example, is specified while infants were moved and the occluding objects remained stationary (see Kellman, Gleitman, & Spelke, 1987). In the course of development, the exploratory activities involved in the obtainment of information become more adapted to the task at hand and the dependency on the task becomes less.

An important difference between cognitive and perceptual views on object knowledge appears to be the extent to which one conceives task variation of principal importance to the outcome of processes and their development. The cognitive view conceives the processes and their development as principally unrelated to the task at hand. The perceptual view does take task factors and task variation into account, because perception is explicitly conceived as the accomplishment of a perceiver-environment system. Both the environment and the perceiver mutually constrain processes that take place within this system and, therefore, affect what information is obtained (see Gibson, 1979). Obtainment of unity information under increasingly varying task conditions would reflect the differentiation with which perception might develop.

Perception of object unity and its persistence may be why infants can perceive the numerosity of a collection of objects and anticipate the outcome of changes in numerosity. For example, if infants are able to perceive the unity of each object of a pair of objects when they move independently and from time to time occlude one another, it may be hypothesized that infants can also perceive the numerosity of this collection. Numerosity perception would then also imply the obtainment of information. At least it would imply the obtainment of information that specifies the unity of elements over space and time. So far there is no clear evidence that infants perceive the numerosity of a collection of elements on the basis of unity information.

Although the processes involved in object perception may form a basis for numerosity perception, other processes must also be involved in determination of the numerosity of objects. Infants may have developed the processes to detect the unity of objects, but, in addition, they should develop processes in which the quantity of objects is apprehended.

The development of number knowledge

When children start to learn number names, they probably rely on an implicit understanding of numerosities that has been developed in infancy. Given existing empirical evidence, this understanding includes at least apprehension of the numerical size of collections of objects (Starkey & Cooper, 1980; Strauss & Curtis, 1981) and of its change when objects are added or deleted (Starkey, 1992; Wynn, 1992a). There is less evidence whether the preverbal number understanding in numerosity perception may involve similar processes as those involved in later achievements, such as in verbal counting. We will assume some continuity between previous and subsequent skills such that verbal counting builds on information sampled in numerosity perception. This continuity may be apparent in similarity of the entities detected and of the processes involved in the detection of these entities.

Proponents of the counting model argue that this continuity is based on counting principles that are already present in early infancy. The counting model of Gelman, Gallistel and their colleagues (Gallistel & Gelman, 1990, 1992; Gelman, 1982, 1990; Gelman & Greeno, 1989) suggests that, analogous to language, number development is a specific, natural domain with its own foundation. They propose that the nature of this foundation is essentially unitary and cognitive, and would guide numerosity perception. Numerosity perception in infancy forms the foundation for verbal counting to develop. The concept of number young children have consists of a group of counting principles that define correct verbal counting as well as non-verbal counting. Within this model three principles of how to count have been defined. The one-to-one principle states that items to be counted must be put into one-to-one correspondence with members of the set of verbal or non-verbal tags. The stable-order principle states that the number tags must have a fixed order in which they are consistently used. Finally, the cardinality principle states that the last tag used in a count represents the cardinality of items.

Two sources of evidence are proposed as support for the hypothesis that counting principles are already present in infancy when infants perceive numerosity. First, Starkey and his colleagues (Starkey, Gelman, Spelke, 1983; Starkey, Spelke, & Gelman, 1990) argue that their findings of infant's numerosity perception indicate the innateness of the one-to-one principle. In particular, the finding that infants perceive the numerical correspondence between elements presented visually and auditorily would suggest this. Second, the early development of arithmetical abilities in children is taken as evidence for an early foundation of the stable-order principle of counting (Gallistel & Gelman, 1990). It is supposed that arithmetic is based on understanding of order relations across numerosities.

The counting model of Gelman and its implications for verbal counting have not remained unchallenged. Fuson (1988) clearly showed that counting does not develop as a unitary numerical skill. Verbal counting of a row of objects involves the coordination of several skills which do not develop simultaneously. While counting children are engaged in labelling of number words and pointing to objects. These different skills need to be coordinated in the course of development. In fact, the skill that may be regarded as basic to Gelman's counting model is acquired relatively late compared to other counting skills. This skill involves children's understanding that number words represent the numerosity of objects. But, initially, 2-year-old children do not appear to know that counting specifies the numerosity of a collection of objects (Fuson, 1988; Wynn, 1990, 1992b). Children learn to count before they understand that the last verbal tag in counting is uniquely tied to a particular numerosity. In other words, children initially do not understand what counting affords. This understanding has to acquired and the findings suggest (e.g., Wynn, 1992b) that it takes children about a year only to learn to specify small numerosities by their unique number names. If these findings are robust, we may conclude that children seem to acquire explicit understanding of what counting is for in the transition from numerosity perception to verbal counting.

Also, the implications of Gelman's counting model for numerosity perception have not remain unchallenged. Strauss and Curtis (1984) argue that infants do not possess some type of rudimentary counting ability. They view counting as, at least sequentially, ordered and affording a final tag that is specific for the numerosity involved. In their view, the existence of these counting principles in infancy is not supported by the evidence on numerosity perception. For example, numerosity perception does not seem to be affected by the arrangement of elements whereas verbal counting is easily affected by children's need to tag objects. Also, the general finding that numerosity perception in infancy is limited to a perceivable range of about one to four elements suggests to them that numerosity perception is fundamentally different from counting. Counting is widely conceived to be a skill that essentially affords the detection of number without an upper limit.

Although numerosity perception does not seem to be guided by counting principles as proposed by Gelman (e.g., Gelman, 1982), counting may be viewed as an extension of numerosity perception (see Smitsman, 1994). Verbal counting may share general processes with the earlier ability of numerosity perception. These processes involve activities of the perceptual system and have to do with the systematic and sequential visual exploration of a collection of discrete elements such as objects.

Counting differs then from numerosity perception in that a system of infinite and ordered counting words uniquely maps onto the sequential exploration of a number of objects in such a way that the last counting word specifies the number. Because counting words uniquely specify all numerosities, they afford communication about numerosities between people.

As an extension of numerosity perception, counting provides new means to overcome the limits of perception of numerosities. These limits are investigated in a series of studies in this thesis. We hypothesize and will attempt to demonstrate that these limits are constraints on object perception and have simply to do with the amount of units an infant can apprehend unaided by a system of symbols.

The studies

Our discussion about current models of object perception and number development indicates that a relation may exist between them, but that the precise nature of this relation is not clear. In the present thesis, we attempt to clarify this relation by investigating the initial numerical abilities of infants. Essentially, we assume that the foundation for processes in determining numerosity of collections of objects are perceptual and not cognitive, and are guided by information obtained over time from displays, and not by principles stored in concepts. By providing evidence about the early development of numerosity, we may be able to demonstrate that apprehension of numerosity involves perceptual activities that are attuned to information about the unity and persistency of objects. If the units are detected, numerosity can be perceived. We assume that numerosity is perceived by the way perceptual activities keep track of units over time and space. Units may accumulate to numerosity dependent on the organization of perceptual activities for a collection of objects. If the organization of these activities differs for different numerosities, it may specify numerosity.

We hypothesized that the perception of the numerosity of a collection of objects involves exploratory activities over time which are focused on unity information. Therefore, it was important to present displays to infants that allowed them to obtain this information. In addition, we wanted to show that numerosity perception for objects is based on the accumulation of units over time rather than their arrangement or patterns over time. Across our studies, therefore, we presented objects under motion that followed irregular and changing trajectories.

We conducted a series of four separate studies. Two investigated whether infants perceive numerosity as an invariant property of a collection of objects that were all simultaneously present. The invariant property of numerosity was specified because the motions change the patterns objects form but leave their numerosity constant. Another series of two studies investigated whether infants perceive numerosity for collections of objects that change in numerosity over time. In these studies, a new object was added to objects already present. If infants perceive what happens to a numerosity during an addition event, they are able to discriminate among the transformations that have no effect on the size of a collection of elements (e.g., change in pattern) and that change the size of a collection (e.g., addition). Discrimination between numerically relevant and numerically irrelevant transformations forms the basis of any numerical ability (Gelman & Gallistel, 1978; Piaget & Szeminska, 1941).

In our studies, we used the well known habituation-dishabituation of visual looking time procedure. This procedure involves infant's familiarization to a particular display until habituation of visual looking times occurs and, subsequently, separate testing of looking times for familiar versus novel displays. It is generally assumed that infants will look longer at displays that they perceive to be new compared to familiar displays. The habituation-dishabituation procedure has been extensively used and studied (e.g., Bornstein, 1985; Cohen & Gelber, 1975; Colombo, 1995; Werner & Perlmutter, 1979). This procedure is generally considered to be a reliable and valid procedure to measure infants' discrimination. The habituation of visual looking time procedure has provided many consistent findings within the domain of infants' visual perception. These findings were replicated with the same procedure and generally provided evidence that converged with procedures consisting of various other measurements, such as saccadic eye movements (Banks & Salapatek, 1983), reaching (Yonas & Granrud, 1985), and visually evoked potentials (Karmel & Maisel, 1975).

Using the habituation of visual looking time procedure in the first study, we investigated whether discrimination of unity of objects, rather than perception of characteristic patterns across objects, underlies numerosity perception. Numerosity was defined as an invariant property of a collection of objects specifying its numerical size. Infants looked at displays of small numerosities (1 to 4 elements) on a TV monitor. The displayed figures moved continuously and at a constant speed. The trajectories were irregular and could produce occlusion of figures. By these occlusions, figures behaved as objects. We introduced as much variation across trials as possible to preclude the possibility that infants would attune to other properties of the display than numerosity, such as amount of contour. Previous research (e.g., Karmel & Maisel, 1975) has shown how sensitive infants are to these properties.

In the second study, we investigated the process by which distinct elements are accrued to numerosity. According to some cognitive views (e.g., Klahr, 1984a; Galloway, 1992), this occurs on the basis of similarity of the shapes. Essentially, these views assert that categorization lies at the basis of numerosity perception and that numerosity is a constitutive feature of the ability to represent a particular category of objects (e.g., dogs). By contrast we assumed that similarity and dissimilarity across objects does not form the basis on which exploratory activities detect numerosity. Instead, we hypothesized that detection of unity information is sufficient for the exploratory activities involved in numerosity perception to emerge. By these activities, an infant may keep track of the numerosity of a collection of objects over time. We examined infants' visual perception of numerosity as an invariant property of a small collection of independently moving, heterogeneous objects that differed in size and shape. The task employed and displays used were similar as in the first study.

In the third study, we investigated whether infants perceive addition of a new element to a collection of elements already present. Specifically, we tested the cognitive view that predicts that infants perceive addition on the basis of components that constitute a complete addition event. Such an addition event occurs, if, for example, there is one object to which one object is added. This event results in a new collection of two objects. Three components may be distinguished that determine the outcome of the addition event. They are the initial collection of elements, the adding and the number of elements that are added.

Finally, our fourth study investigated whether infants can perceive the outcome of an addition that involves the addition of one object to another object already in a container. If understanding of addition is based on a cognitive computing process, one would predict on the basis of previous findings (e.g., Wynn, 1992a) that infants can anticipate the numerical outcome of the addition in the container. If understanding of addition is based on exploratory activities that infants employ while keeping track of the elements in an addition, these activities are, perhaps, constrained by the type of changes that constitute the addition.

2 Study I: Visual Perception of Numerosity in Infancy[1]

Numerosity was defined as an invariant property of a collection of objects specifying its numerical size. Infants looked at displays of small numerosities that changed optic structure such that size was not tied to certain static or dynamic configurational properties of the display, but remained constant across patterns of optic motion. The displayed figures moved continuously at a constant speed. The trajectories were irregular and could produce occlusion of objects. The task used involved infant-controlled habituation of visual looking-time. At ages 5 months, 8 months, and 13 months, 44 infants were tested for the numerosities 2, 3, and 4 in three randomly ordered sessions. The results demonstrated that infants from the age of at least 5 months perceive small numerosities. It appears that discrimination of units, rather than discrimination of characteristic patterns, underlies numerosity perception.

Introduction

Numerosity may be conceived of as an invariant property of a collection of objects specifying its numerical size. Numerosity remains constant across variation in nearly all of a collection's dimensions, such as change in type and arrangement of objects. In other words, numerosity remains constant as long as no objects are added or deleted. The question of whether infants are able to perceive numerosity and the size up to which

[1]This chapter has been published as van Loosbroek, E & Smitsman A.W (1990) Visual perception of numerosity in infancy Developmental Psychology, 50, 916-922.

they can perceive was the subject of a series of studies. These studies revealed that infants from at least 4 months of age perceive the numerosity of small groups of objects containing up to about four elements (Curtis & Strauss, 1983; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1983; Strauss & Curtis, 1981; Treiber & Wilcox, 1984). Infants were habituated to static displays of small collections of elements (from 1 to 4 elements) and, after habituation, were presented with novel collections that could be either smaller or greater in numerical size than the ones seen previously. Typically, the collections varied in density, configuration, color, or contour of the elements and therefore the results must be attributed to change in numerosity and not to changes in non numerical properties such as density. Although there is clear evidence that infants can perceive the numerical size of small collections of objects, the precise nature of this ability and how it develops are less clear. What is the information that enables infants to abstract numerosity and how is this information detected? These questions need to be considered to gain insight into numerical abstraction in infancy. Two views exist with respect to these questions.

In one view, development of numerosity perception is conceived of as a pattern perception process involving the discrimination of static configurational properties (see Mandler & Shebo, 1982; von Glazersfeld, 1982). This view suggests that configurational properties form the informational basis for numerosity because each of these small sizes is generally tied to some typical spatial arrangement, such as twoness to a line and threeness to a triangle. There is a problem with this view, however. Although configurational properties may be easily abstracted by infants, these properties are ambiguous with respect to numerical size. The spatial arrangement of a collection of objects can be changed while numerosity is left unchanged. In fact, in the studies cited above, the static arrangement of objects was varied across trials, and the results nevertheless indicated that infants perceived the numerosity of a collection. Thus, it may be concluded that spatial properties do not form the sole informational basis for infants' numerosity perception.

According to another view, numerosity perception in infancy may reflect some rudimentary form of counting (Gelman, 1982; Starkey, Gelman, & Spelke, 1985). Little systematic research exists in favor of this hypothesis. Moreover, how this non-verbal counting is accomplished and to what extent it already incorporates principles found in the counting behavior of older children remain unexplained. But if infants perceive the numerosity of objects by some ability akin to counting, it may be argued that this ability must be based on discrimination of each of the elements involved rather than on some overall dimension of the collection, such as its pattern. More specifically, apprehension of numerosity requires at least the discrimination of countable units, that is, objects or surfaces that posses the properties of unity and boundedness. By their unity and boundaries, objects afford perception of their numerosity, as opposed to substances such as water, which does not consist of discrete units and hence does not specify numerosity.

Whether it is the pickup of information about units or information about configurations that enables numerosity perception may be tested by presenting infants with displays of small collections of objects that move around continuously and occasionally form partial occlusions. Static configurational properties are thus no longer present then. However, motion displays can specify dynamical patterns across elements that are sometimes easily perceived by infants (see Bertenthal, Proffitt, & Cutting, 1984). Therefore, the objects presented should not only change position continuously but also move independently along different trajectories so that variation in motion patterns is maximized over time. This procedure also ensures that unity of each object is specified, because series of experiments have shown that independent movement of an object undergoing partial occlusion provides optical information to infants about the unity of this object (Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986; Spelke, von Hofsten, & Kestenbaum, 1989). Consequently, one may assume that the ability to segregate more than one object in a visual array is based on the same principle. Thus, specification of two or more units is achieved when objects move continuously and independently.

While objects are moving, the unity of each object, but also the invariance of numerosity, is specified until objects are added or deleted from the collection (Smitsman, 1985). The purpose of the present study was thus to investigate whether infants perceive numerosity invariance over arrays of continuously moving objects. Given the findings that infants can discern numerosities of small static groups of elements and also detect the discreteness of an object over movement, we expect that infants would be able to perceive the constancy of small numerosities. To test this hypothesis, we designed a short term longitudinal study in which age range (5 to 13 months) and collection sizes (2 to 4 elements) were comparable with those used in the static numerosity research.

In a visual habituation procedure, infants were habituated to displays of small numerosities that changed the optic structure such that numerosity was not tied to certain static or dynamic configurational properties of the display but remained constant across patterns of motion. The displays, which were presented successively, consisted of figures that moved in translation at a constant speed and followed different, independent trajectories. After visual attention had decreased to a certain criterion, a novel numerosity was displayed that could be either greater ($x+1$) or smaller ($x-1$) than the numerosity in the habituation phase, depending on the condition to which infants were assigned. We reasoned that if infants were able to discriminate between small numerical quantities, they would show prolonged attention to a novel numerosity.

Method

Subjects

Subjects were 30 infants who were tested when they were 5 months old (mean age = 23.5 weeks), 8 months old(mean age = 36.1 weeks), and 13 months old (mean age = 58.2 weeks). At each age, they were to complete three sessions within about one week. We started out with a group of 55 infants of 5 months old, but 11 infants at that age were excluded due to fussiness at two sessions. At 8 months of age, another 5 infants were excluded from the final analyses because parents did not want to participate anymore or had moved (3 cases) and because infants became fussy or fell asleep at two sessions (2 cases). At 13 months of age, 9 infants were excluded because of fussiness or sleep at two sessions or because of removal or refusal to participate. Infants who were excluded from the longitudinal analyses at a particular age were still tested at other ages. They could be assigned to a comparison group at any other age if they completed three sessions at that particular age. In addition to these infants, comparison groups for the three age levels consisted of infants from the longitudinal group; they were used to measure attrition effects. Names and addresses of infants were obtained from the municipal government in Nijmegen, and infants participated after informed consent by the parents. Parents were paid for their participation.

Procedure

At each age, each infant was tested for the numerosities 2, 3, and 4 in three separate, randomly ordered sessions. The procedure was the same for all sessions at all ages. Infants were seated on the laps of their parents or caretakers, who were uninformed about the procedure and were instructed not to look at the display. Nevertheless, some parents did look occasionally but, on inquiry, never appeared to be aware of differences between numerosities within a session. Infants were shown patterns of 2, 3, and 4 rectangular figures that moved continuously on a 16 x 24 cm black-and-white TV. monitor approximately 80 cm in front of them. Figures were 3.3 x 2.3 cm large and consisted of matrices of 16 x 16 elements that were filled in varying degrees of density ranging from 40% to 83%, with an average of 61%. Examples of these figures are depicted in Figure 1, which shows a minimum, a maximum, and average filling. Within this range of filling, 37 figures were constructed.

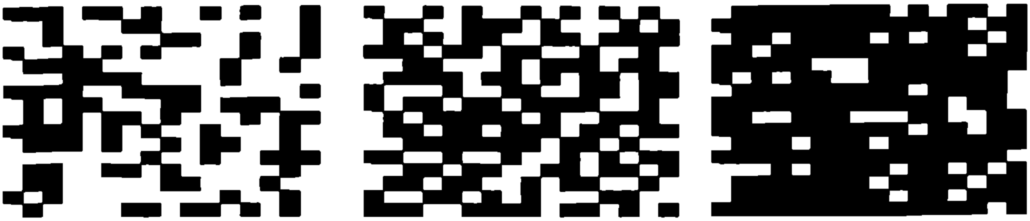


Figure 1 Examples of displayed figures.

The variation in figures involved the restriction that, except for the numerosities 2 and 1, greater numerosities in a session (e.g., 4) had to consist of at least two less densely filled figures and smaller numerosities (e.g., 3) had to consist of one densely filled figure. Seventeen gray-colors were used to display figures.

An earlier study (van Loosbroek & Smitsman, 1989), in which objects moved at the same rate along linear trajectories, suggested that it was important for infants' perception of numerosity to eliminate any coherences between movements and to make trajectories as independent as possible. The 11 movements we selected according to this criterion progressed at a constant rate (albeit different across movements) along curvilinear trajectories at varying orientations (see Figure 2). All movements consisted of trajectories of 200 coordinates that were repeated every 12 seconds. Therefore, the periods of rotation for the different movements were always the same, but the distance traversed within a period differed somewhat.

Movements could produce occlusions of objects that differed in degree of transiency and completeness. When two objects were displayed, for example, trajectories were selected from 53 different movement combinations, 22 of which showed an occlusion consisting of more than 10% overlap of the figures and lasting for more than 15 out of 200 coordinates in one period, with a maximum of 100. These combinations formed the basis for the movements of numerosities 2, 3, and 4.

The average and range of the number of occlusions for the novel numerosities were the same as those for the old numerosities, because movements for a greater numerosity (either an old one or a novel one) were always selected in accordance with a random sample of occlusions generated by the movements of the smaller numerosity. For example, if four objects were displayed in the habituation phase and five in the test phase, the number of occlusions for both numerosities ranged from zero to five occlusions, with an average of about three. The sessions with the numerosities 2 and 1 were an exception to this rule and differed in number of occlusions.

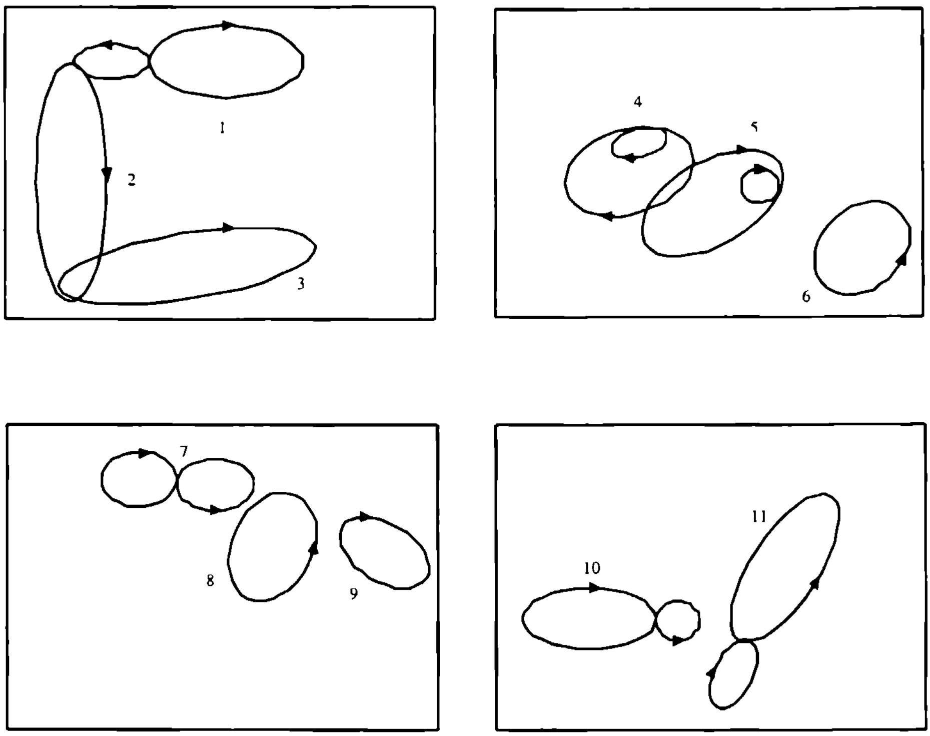


Figure 2. Schematic representation of random combinations of the object trajectories 1 to 11.

In each session, movements were selected from arrays of 250 movement combinations. Across this total, the numerosities 2 (in sessions 2-3 and 3-2), 3 (in sessions 3-4 and 4-3), and 4 (in sessions 4-5) generated 97, 185, and 242 occlusions, respectively. Only 2% of the coordinates for numerosity 3 and 4% of the coordinates for numerosity 4 consisted of three figures simultaneously forming an occlusion. Although the number of occlusions did not generally differ for two numerosities in a session, duration and amount of overlap of the figures could vary because occlusions were not based on the same movements. This variation, however, was random and not systematically tied to greater or smaller numerosities. The movements, occlusions, figures, and gray-colors were varied as much as possible for habituation and test trials so that pattern, number of occlusions, area and amount of luminance changed over all trials and not only when numerosity was changed. These variations render implausible the possibility that any other factor than numerosity might account for the results. The figures, movements, and gray-colors were generated through the use of sprite graphics on an Apple IIe computer (see Bertenthal & Kramer, 1984).

A variation of a task involving infant-controlled habituation of visual looking time (Horowitz, 1974) was used which was assisted by the computer. The beginning of each trial was signaled by a tone. A trial was ended after an infant had looked for at least for 1 s and had then continuously looked away for 2 s. In between trials, the monitor was empty for about 6 s. The first three trials of the habituation phase were used to compute the habituation criterion. The criterion was half of the mean fixation time on these first three trials. After this criterion was reached on three consecutive trials or after a maximum of 23 trials, a test phase was started consisting of four trials: two old (O) trials and two novel (N) trials. On O trials the numerosity of the habituation phase was again presented. On N trials a novel numerosity was presented, either x-1 or x+1, depending on the condition to which the child was assigned over age. For example, when on O trials two figures were displayed, there would be three figures on N trials in condition x+1 and one figure on N trials in condition x-1. Test trials were presented in two different orders: O-O-N-N or N-N-O-O. Order of test trials was randomized across sessions and over age. Order of sessions (2, 3, and 4) was varied across infants and over age.

Looking times were recorded in tenths of seconds by an observer who viewed the infants through holes in a curtain under the monitor. The observer was unable to see the display and thus had no knowledge of when the test phase started. In part of the complete sessions over all ages (i.e., 60 sessions) infants were viewed by two observers to determine agreement of observation. Interobserver reliability on 0.5-s intervals of total looking time over trials averaged 94%.

Whenever an infant became fussy or fell asleep during the habituation trials, the experiment was interrupted for a short time and resumed if possible. If an infant became fussy or fell asleep after the last habituation trial, the session was stopped. No more than one break per session was allowed.

Results

In the analyses, combined fixation times for both N trials were always compared with the combined fixation times of the two preceding trials. That is, for the O-O-N-N order these trials were the two preceding O trials in the test phase. For the N-N-O-O order, however, these trials were the last two trials in the habituation phase rather than the two subsequent O trials in the test phase. In the case of the N-N-O-O order, we used a statistical procedure to estimate the spontaneous recovery in fixation times of the N trials compared with that of the two preceding (the last two habituation) trials (see Bertenthal, Haith, & Campos, 1983). The spontaneous recovery in fixation time that was found between the last two habituation trials and the two subsequent O trials in the O-O-N-N order was added to that of the last two habituation trials of the N-N-O-O order. These estimated recovery scores were computed for each age.

Visual fixation times were transformed to proportion scores by dividing both the combined fixation times on the last two old numerosity trials and the combined fixation times on the two novel numerosity trials by two thirds of the combined fixation times on the three trials preceding the test phase. When, for example, a proportion score for the N trials was larger than 1, it indicated that the mean looking time of these two trials was larger than the mean looking time of the last three habituation trials. Because the data for the repeated measurements violated the circularity assumption of a mixed univariate analysis of variance (ANOVA), multivariate analyses of variance (MANOVA) were performed (Hertzog & Rovine, 1985). To test the principal question of whether infants discriminated between novel and old numerosities, a MANOVA was conducted on the proportion scores with the factors type of novel numerosity (x-1 or $x+1$), age (5, 8, and 13 months), numerosity (2, 3, and 4), and trial (habituation and test), the last three of which were within-subject factors (see Table 1 for the means). The MANOVA yielded a significant main effect of trial, F (1,28) = 17.06, p < .001, that was qualified by a significant Age x Trial interaction, F (2,27) = 3.87, p < .05. No other main effects or interactions were significant.

Table 1. *Combined Transformed Mean Fixation Time Scores for Type of Novel Numerosity (x-1, x+1)*

		Numerosity					
Age	Trial	2	3	4	2	3	4
			x-1			x+1	
5 months							
	Old	1.066	1.314	1.975	1.284	1.412	2.310
	Novel	1.468	1.797	1.751	2.193	1.848	1.652
8 months							
	Old	1.296	1.250	1.054	1.128	1.105	1.332
	Novel	2.300	2.047	2.373	1.664	2.052	2.000
13 months							
	Old	2.135	1.505	1.903	1.850	1.634	1.519
	Novel	2.441	3.449	2.767	2.309	3.013	1.882

Note. The number of subjects in each cell is 15.

Additional comparisons (following Mitzel & Gamus, 1981) were performed at each age to investigate the locus of the Age x Trial interaction. No main effect of trial was found at 5 months, $F(1,14) = 0.34$, whereas at 8 months reliably greater fixation scores were found for N trials than for O trials, $F(1,14) = 9.88$, $p < .01$. Although the means of the N trials were always greater than those of the O trials, no significant effect of trial was found at 13 months, $F(1,14) = 2.21$, $p > .10$. To further explore these results, proportion scores at each age were entered separately into a type of novel numerosity (*x-1* or *x+1*), numerosity (2, 3 and 4) and trial (old and novel) MANOVA. Overall, only two main effects were found: trial at 8 months, $F(1,28) = 13.67$, $p < .001$, and trial at 13 months, $F(1,28) = 5.47$, $p < .05$. The trial effect at 5 months did not approach significance, $F(1,28) = 1.28$, $p > .2$. The high within-cells variance at 13 months, four times higher than at 8 months of age, explains why no significant result was found with a conservative a posteriori test. This kind of reasoning cannot account for the negative results at 5 months because the variance then was only one and a half times greater than at 8 months.

Table 2. *Combined Transformed Mean Fixation Time Scores for Type of Novel Numerosity (x-1, x+1), for the Complete Group of 5-Month-Olds*

	Numerosity					
Trial	2	3	4	2	3	4
		x - 1			x+1	
Old	1.054	1.033	1.703	1.302	1.277	1.865
Novel	1.255	1.804	1.804	2.806	2.157	1.577

Note. The number of subjects in each cell is 22.

To establish the effect of attrition of infants, we contrasted the data of 5-month-olds from this longitudinal study with the results of the group of 5-month-olds ($n = 44$) with which we originally started (van Loosbroek & Smitsman, 1986). A MANOVA conducted for the proportion scores of the original group[2] revealed only a significant effect of trial, $F(1,42) = 8.84$, $p < .005$, indicating that these 5-month-olds discriminated between old numerosities and novel numerosities (see Table 2 for the means). Comparison of the means for the longitudinal and the original, complete group (see Tables 1 and 2, respectively) suggests that the attrition of subjects generally decreased the difference between scores

[2] There are slight but irrelevant differences between the data and analyses of the complete group of 5-month-olds reported here and earlier (van Loosbroek & Smitsman, 1986). Instead of dividing fixation times on test trials by two thirds of the fixation times of the combined fixation times on the last two three habituation trials, as was done in the present study, times were divided in the previous study by the combined fixation times on those three trials In addition, ANOVAs, instead of MANOVAs, were conducted on the transformed scores, but the results of these two analyses turned out to be generally comparable and, of course, identical for the analysis of the main effect of the between-subjects factor type of novel numerosity, the main effect of trial, and the Trial x Type of Novel Numerosity interaction

on old and novel trials and, especially, had a negative effect on the discrimination between 4 and 3 and 4 and 5, respectively. No differences were found between the original and longitudinal groups at 8 and 13 months of age. In sum, these results suggest that infants from 5 to 13 months old discriminate between small numerosities.

To determine whether the different displays representing the numerosities 2, 3, and 4 were of equal interest and difficulty to the subjects, various analyses of variance were performed on measurements of the habituation phase, with type of novel numerosity (x-1 or x+1) as the between-subject factor and age (5, 8, and 13 months) and Numerosity (2, 3 and 4) as within-subject factors. A MANOVA of the number of habituation trials to criterion yielded a significant effect of age, $F\ (2,27) = 13.01$, $p < .001$, and no other reliable main effects nor interactions, indicating that as infants became older they needed more trials to reach criterion (Ms = 10.1, 13.5, and 14.7 for the ages 5, 8, and 13 months, respectively). A MANOVA of total fixation time on the first trial revealed no reliable main effects or interactions, suggesting that all numerosities initially got equal attention from infants across ages. A MANOVA of total looking time to criterion yielded only a significant effect of numerosity, $F\ (2, 27) = 5.64$, $p < .01$, suggesting that the displays representing the numerosities 2, 3, and 4 differed in interest or complexity. An inspection of the means made it clear that infants looked longer at greater numerosities than at small numerosities (mean fixation times were 165.1, 176.1 and 231.2 s for the numerosities 2, 3, and 4, respectively).

Discussion

This study presents a test of the hypothesis that infants are able to perceive numerosity as an invariant property of a collection of moving objects. The results indicate that infants can indeed abstract the numerosity of small collections of objects over motion, suggesting that discrimination of distinct units, rather than pattern perception, underlies numerosity perception. After habituation to a certain quantity of continuously moving objects, infants generally dishabituated to a novel numerosity that was one greater or smaller than they had previously seen. Specifically, the results within the longitudinal group, together with the difference in results between the complete sample and those of the longitudinal sample of 5-month-old infants, may indicate that perception of numerosity invariance is not very robust at 5 months. Either development is still going on in that not all infants have acquired stable numerosity perception at this age or the experimental procedure that was followed was partly insensitive to 5-month-olds' perceptual abilities. We favor the first interpretation; an inspection of the data suggests some development between 5 and 8 months of age because the range of numerosities perceived seems to extend from 3 (3-2 and 3-4) to 4 (4-3 and 4-5). Also, this limited range of perceivable numerosities was apparent for the longitudinal as well as the original group of 5-month-olds.

The inconsistent results at 13 months of age are not interpreted as evidence for the absence of numerosity perception at that age. On the contrary, because a reliable discrimination was found at 8 months of age, the ambiguous findings at 13 months may be ascribed to problems with the habituation procedure at this age. For example, 1-year-old infants become very mobile and, therefore, often do not want to sit on their parents' laps to look at a display for a long time. This should lead to increasing variance of looking times and, hence, to difficulties in reaching criterion. That this trend exists is buttressed by the finding that older infants reached criterion later than younger infants.

In sum, we conclude that this study presents a demonstration of numerosity perception for collections of moving objects forming transient and partial occlusions. In making this conclusion, we want to argue that explanations for these data involving variables such as pattern, area, or color, rather than numerosity and units, can be ruled out effectively. We should point out that in this study, control for variables other than numerosity was achieved by introducing as much variation as possible in all possible covariables across trials. In this respect, we provided controls similar to those provided in the static numerosity studies. It is acknowledged that complexity in motion displays may covary with numerosity. One important cause of complexity in motion displays is occlusion of objects. Increasing the number of objects that move within a limited field increases the probability of occlusion. Because we held the probability of occlusion constant across old and novel numerosities, this variable cannot account for the dishabituation results of our study. The introduction of movement typically introduces additional variables that can covary with numerosity, such as total path length, but in our opinion the extensive variation of movement patterns and, hence, of total path length adequately controlled for these variables.

The present data do not support the hypothesis that perception of small numerosities can be regarded as a process in which typical spatial arrangements are detected across objects (e.g., 3 is a triangle, Mandler & Shebo, 1982, von Glazersfeld, 1982). In line with such a hypothesis, it is maintained that configurational wholes, and not numerical compounds of units, would be discriminated. Originally this type of pattern perception process was conceived of for static configurations. However, there appears to be no satisfactory dynamic interpretation of this pattern perception process for our displays of small collections of moving objects. To begin with, the characteristics of our display do not allow for the perception of structures moving in depth such, as when objects are spinning, tumbling, or undergoing elastic motions. Objects that move independently and constantly but at different rates in a plane cannot represent a projection of a continuous transformation in three-dimensional space (see Braunstein, 1974). In addition, the occlusion of objects precludes the specification of a continuous two-dimensional transformation of a triangle for three units because the necessary invariant cross-ratio cannot be identified. Similarly, an interpretation of perceptual organization as the sampling of static projections of moving patterns does not work. Conceiving of perception of our displays as involving the association of various typical stationary patterns assumes implicitly that infants are unable to use movement information in object perception. Recent research indicates clearly that infants are quite able to detect information as specified by object movement (e.g., Kellman et al., 1986; Spelke et al., 1989). Moreover, typical patterns were not always present, especially for greater numerosities. For example, when three objects were shown, an average 25% of the time objects were occluded so that only a line, and not a triangle, could be perceived. Presumably, these ambiguities increase the effort involved in such a pattern perception process, and this may be manifested in differences between numerosity perception of stationary objects and numerosity perception of moving objects. But no clear asymmetries have yet been found. Because infants may be able to perceive two units in the projection of two occluding objects (see Granrud & Yonas, 1984), they of course could be granted the additional ability to perceive two units when atypical static patterns are present, because of interposition. This addition would come close to our view that all units, rather than patterns across units, must be discriminated. Still, our view better fits recent models of object perception and has the advantage of consistency and simplicity.

The evidence presented here may be explained by a conception of infants' numerosity perception as reflecting a rudimentary counting ability (see Gelman, 1982; Starkey et al., 1985) if this counting is seen at least as the detection of units. Like counting, numerosity perception involves some sort of tagging to the extent that an infant keeps track of the constancy of numerosity over time. It is questionable, however, whether other component skills of verbal counting can account for the abstraction of the numerical size of a group of moving objects. For example, it has been contended that perception of equality or inequality of numerosities depends on a basic component of counting, that is, abstraction of a one-to-one correspondence. But what should be matched to what and how is this done? Analogous to verbal counting, preverbal "counting" may be assumed to involve essentially an iterative process that is sequential and demands a differentiation of "counted" and "uncounted" items. The implications of such a view have been worked out for static numerosity studies, but little evidence was found to support it (see Strauss & Curtis, 1984). Neither do our results provide evidence supporting the view that perception of small numerosities is sequential and involves detection of order relations across numerosities, as is the case in counting numbers. In conclusion, it appears implausible that all properties of the counting process underlie the ability to abstract numerosity over continuously moving objects. Nevertheless, the evidence remains that discrimination of units is as basic to early numerical development as it is to counting (Fuson, 1988).

Numerosity perception may be conceived of as a visual exploration process that is limited in the range of elements that can be abstracted (see Smitsman, 1982). On the basis of the assumptions of direct perception theory (J.J. Gibson, 1979; Shaw & Pittenger, 1977) and its developmental elaboration (Gibson & Spelke, 1983), one may describe the visual exploration of quantities may be described as the pickup of information specifying that a certain numerosity of a collection of objects remains constant. We wish to argue that the invariant information generated through continuous movement is in principle sufficient to segregate the optic array into distinct units and to permit detection of their numerosity (Smitsman, 1985). Our account of numerosity abstraction as involving perceptual processes making use of the specification of invariant information for unitary objects may be further investigated by testing the effect of heterogeneity of moving objects on numerical abstraction. Such an investigation may provide data consistent with the hypothesis that through perception children acquire some knowledge about how many things there are in spite of ongoing positional transformations. As the present investigation shows, this knowledge is already developed when counting skills become fully available, and it may form the basis on which these skills are developed.

3 Study II: Heterogeneity of Shape in Numerosity Perception

In this study, information that enables infants to visually perceive the numerosity of a small collection of heterogeneous elements was investigated. The task involved infant-controlled habituation of looking time. A display exhibited a small collection of elements moving independently at a constant speed. The trajectories of the elements were curvilinear and could cross. the collections consisted of different numbers of heterogeneous elements that differed in shape and size. Two groups of infants, 5 months old and 13 months old, were tested for the numerosities 2, 3, and 4 in three randomly ordered sessions. The results showed both age groups to perceive numerosity. In addition, there was an effect of heterogeneity of shape but only at 5 months and only for the numerosity 2. Perception of numerosity appears to involve search processes that accumulate distinct elements on the basis of their unity information.

Introduction

In several studies, infants from 4 months of age have been found capable of perceiving the numerosity of small collections of up to about four elements (e.g., Starkey & Cooper, 1980; Strauss & Curtis, 1981; Treiber & Wilcox, 1984). These findings gave rise to the question of how infants can visually perceive numerosity. What is the invariant property of small collections of elements that specifies their numerical size? Which information do infants obtain that enables them to perceive numerosity?

We have found numerosity to be perceived for not only static displays but also displays with moving elements and thus configurations that change continuously (van Loosbroek & Smitsman, 1990). In our study, the displayed elements behaved as objects because they moved independently and occasionally formed partial and temporary occlusions. The motion specified the unity and boundedness of each element. These results thus suggest that infants are capable of perceiving the numerosity of small collections of independently moving figures precisely because they pick up information with regard to the distinct elements.

If information about the unity of specific elements provides the basis for the perception of numerosity, we still do not know the mechanism responsible for the accrual of elements to numerosity. One mechanism that has been suggested is some kind of categorization process in which the infants discern the elements joining together to constitute the collection and thus the numerosity (Klahr, 1984a, 1984b). Given sufficient similarity of shape, for example, infants might categorize the available elements and thereby perceive the numerosity of the collection. In other words, numerosity may initially be perceived for only highly similar elements, for example, when they are homogeneously shaped. At first, infants might perceive numerical size for only such homogeneous collections as three blocks or three rings. Gradually, through a process of generalization, infants might also perceive numerosity for a collection of heterogeneously shaped elements. Threeness, for example, might then be abstracted as an invariant property that is shared by collections of differently shaped elements. Klahr's position implies that similarity of shape may facilitate the detection of numerosity by young infants and that heterogeneity of shape may hamper such detection.

We, however, see no logically compelling reason for similarity of shape to be abstracted for numerosity as it is for categorization. By itself, shape bears no relation to numerosity. The size of a collection can change without the similarity in shape changing, and a change in similarity does not necessarily affect the size of a collection. The size of a collection only changes when distinct elements are added or deleted. Even in the perception of an element as distinct, moreover, information about shape does not appear to play a necessary role. Perception of a distinct element, such as an object or figure, involves perception of its unity as Spelke (1990) has shown. Such perception does not entail an analysis of shape and the elements may therefore be perceived as formless. In conclusion, we argue that numerosity can be detected without the pickup of similarity information specified by shape.

Our previous study showed infants to perceive numerosity across spatial transformations induced by the independent motion of constantly present the elements. As the elements were always rectangular and of the same size, no evidence is as yet available with regard to the perception of numerosity for a collection of heterogeneous, independently moving elements. We only know that infants are able to perceive the shape of an element moving translationally (Byrne & Horowitz, 1984; Day & Burnham, 1981; Slater, Morrison, Town, & Rose, 1985) at the age at which we have demonstrated numerosity perception (i.e., 5 months).

In studies of numerosity perception for static displays, no clear effect of heterogeneity of shape was demonstrated for either 5- or 13-month-old infants (Curtis & Strauss, 1983; Starkey et al., 1990). The only effect of heterogeneity of shape has been found in a study with 13-month-old infants by Strauss and Curtis (1981). Whereas infant girls only discriminated between arrays of 3 and 4 homogeneous elements, whereas infant boys did exactly the opposite and only discriminated between 3 and 4 heterogeneous elements. It should be noted that they did not find this effect at 5 months of age (Curtis & Strauss, 1983) and did not provide any explanation for these complex results.

A study that combines elements moving independently and heterogeneous in shape may provide further insight into the mechanisms responsible for numerosity perception in infancy. We therefore investigated whether infants are able to perceive the numerosity of small collections of moving elements (2 to 4 elements) that clearly vary in shape and size. In order to facilitate comparison to our longitudinal study of numerosity with homogeneous elements (van Loosbroek & Smitsman, 1990), infants were tested cross-sectionally at the two extremes of the age range investigated previously. Moreover, we generally employed the same design and habituation procedure as in the previous study.

Method

Subjects

The subjects were 24 infants of 5 months of age (mean age = 21.3 weeks) and 24 infants of 13 months of age (mean age = 59.7 weeks). There were initially 30 infants in the first age group but six were excluded due to fussiness or sleepiness during two sessions. There were initially 27 infants in the second age group but three were excluded. The names and addresses of the infants were obtained from the municipal government in Nijmegen. The parents were contacted by letter and, after consent, by telephone. No specific criteria for admission were used. Parents were paid for participation.

Procedure

The infants were tested individually for the numerosities 2, 3, and 4 in three separate, randomly ordered sessions spread across an interval of generally seven working days. The sessions were never on the same day. The procedure was the same for all sessions and both ages. The infants were seated on their parents' or caretakers' lap in a dimly lit room at the university. The parents were asked not to look at the display. The infants' view of the environment was limited by screens surrounding the display. Infants sat facing a 16 x 24 cm black-and-white TV monitor approximately 80 cm in front of them.

Figure 3. Examples of heterogeneous figures.

Infants looked at patterns of 2, 3, and 4 figures moving continuously on the monitor. The figures ranged from about 3.3 x 2.3 cm to 2.7 x 1.7 cm in size. The total sample consisted of 36 figures and was generated by combining twelve different shapes and three different sizes (see Figure 3 for examples). The shapes were irregular. In those sessions in which the infants habituated to 2 figures and then shown 1 figure in the test phase (i.e., numerosity combination 2-1), the choice of figures was random. In other sessions with greater numerosity combinations than (2-1), the choice of figures was restricted in order to be sure that on the average the overlap of figures was the same for different numerosities in the habituation and test phases. For these numerosity combinations, two of the figures of greater numerosities per session (e.g., 4) were specifically chosen to be small; the remaining choices were random. For the smaller numerosities in a session (e.g., 3), one figure was specifically chosen to be big; the remaining choices were random. The figures were displayed in one of seventeen gray-colors, and the background in a different gray-color. All colors were translucent; that is, they showed the color and shape of the occluded figure when two figures overlapped. The shape and gray-color of the figures varied independently for each trial.

In order to maximize the information about the unity of each figure and minimize the information about pattern, the figures were displayed with independent, curvilinear movement. This is the same as in study I (see Figure 2 in Chapter 2). The figures moved at a constant speed but with different velocities along different curvilinear trajectories. Eleven curvilinear trajectories that differed in the orientation of their axes to the monitor, the degree of flatness, and the direction of rotation (clockwise or not) were used. In addition, six of the eleven trajectories were compounds of two curvilinear patterns (e.g., a large and a small ellipse). It took 12 s to complete a full trajectory which always involved 200 coordinates.

We used the same 53 movement combinations as in our first study of figures homogeneous in size and shape. These movement combinations generally had been found to make the number of occlusions relatively constant across the presentations for two different numerosities. Since figures were now different in size and shape , we had to establish whether amount and length of occlusion did not differ for different numerosities in a session due to the combination of movements and heterogeneous shape of the figures. We measured occlusion over a total of 250 cycles, each cycle consisting of a complete movement of 200 coordinates. Amount of overlap was defined as any overlap as small as 1 pixel (with a figure composed of a possible maximum of 254 pixels). The length of overlap was defined in terms of how many coordinates the occlusion lasted (with 200 coordinates constituting a single cycle). The amount of overlap per complete movement was found to somewhat vary across the different numerosities but the overlap across different movement trajectories per numerosity was found to vary much more. This variation is even greater in real testing because figures are not presented then during complete trajectories but only during part of these movements. We therefore concluded that the variation in the overlap for the different numerosities was unlikely to influence looking behavior of the infants.

An infant-controlled habituation of visual looking time task was used. The beginning of each trial was signaled with a tone. A trial ended when an infant had made a total of ten fixations or the total looking time exceeded 1 s and the infant subsequently looked away for 2 continuous seconds. The habituation criterion was half of the mean fixation time for the first three trials in the habituation phase. After this criterion was reached on three consecutive trials or after a maximum of 23 trials, the test phase began. The test phase consisted of four trials: two old (O) numerosity trials and two novel (N) numerosity trials. On the O trials, the numerosity from the habituation phase was again presented (i.e., $x = 2, 3,$ or 4). On the N trials, a novel numerosity was presented which was either one less (x-1) or one greater ($x+1$) than the old numerosity from the habituation phase. Child were randomly assigned to the condition of type of novel numerosity (x-1 or $x+1$). The O and N trials were presented in two different orders: O-O-N-N or N-N-O-O. These orders were randomized across the sessions. The order of sessions (2, 3, and 4) was also randomly varied across the infants.

Looking times were recorded on-line by an observer through viewing holes in a curtain under the monitor. The observer was unable to see the display and was thus unaware of when the test phase began. The observers used a button box, which was connected to a computer. Trained observers with an average inter-observer reliability of 94% on 0.5-s intervals across trials were used. Whenever an infant became fussy or fell asleep during the habituation trials, the session was interrupted for a short while and resumed if possible. If an infant became fussy or fell asleep in the test phase the session was stopped. No more than one break per session was allowed. A session that had been stopped could be repeated at a later date, but only one session per subject could be rerun. Three percent of the analyzed sessions had been rerun.

Results

In accordance with our previous study, the comparisons always involved both of the N trials with the two preceding trials. For the O-O-N-N order, these trials were the two preceding O trials in the test phase. For the N-N-O-O order these trials were the last two trials in the habituation phase rather than the two subsequent O trials in the test phase. In the case of the N-N-O-O order, we used a statistical procedure to estimate the spontaneous recovery in fixation times for the N trials compared to the two preceding trials in the habituation phase (see Bertenthal et al., 1983). The estimated spontaneous recovery in fixation time that was found between the last two habituation trials and the two subsequent O-trials in O-O-N-N order was only added to the last two habituation trials of the N-N-O-O order. These estimated recovery scores were computed for each age.

Also in accordance with our previous study, we transformed visual fixation times in order to equalize the variances of the data. The visual fixation times were transformed to proportion scores by dividing the combined fixation times for the two O (i.e., old numerosity) trials and the combined fixation times for the two N (i.e., novel numerosity) trials by two thirds of the combined fixation times for the three trials preceding the test phase.

Table 3 *Combined Mean Transformed Fixation Time Scores for Old Numerosity (x = 2 3 4) and Type of Novel Numerosity (x-1 x+1)*

		Numerosity					
Age	Trial	2	3	4	2	3	4
			x-1			x+1	
5 months							
	Old	1 066	1 314	1 975	1 284	1 412	2 310
	Novel	1 468	1 797	1 751	2 193	1 848	1 652
13 months							
	Old	2 135	1 505	1 903	1 850	1 634	1 519
	Novel	2 441	3 449	2 767	2 309	3 013	1 882

Note The number of subjects in each cell is 12

A MANOVA for a repeated measurements design was used to test whether infants discriminated between numerosities. Separate MANOVAs were conducted on the proportion scores at each age with the between-subjects factors type of novel numerosity (*x-1* or *x+1*), numerosity (x = 2, 3, and 4) and the within-subjects factor trial (old and novel) (see Table 3 for the means) The MANOVA for 5-month-olds yielded a significant Numerosity x Trial interaction, F (2,21) = 3.99, $p < .05$. This indicates that infants' dishabituation to novel numerosities was dependent on the numerosity displayed Comparisons (cf Mitzel & Games, 1982) using the Bonferroni procedure (a = .017) at each of the three Numerosity x Trial combinations revealed only a significant effect for numerosity 3 At 13 months of age, the MANOVA revealed a significant main effect of trial, F (1,22) = 8.02, $p <$ 01 This indicates that infants discriminated between numerosities. Comparisons (a = .017) did not reveal significant results for any of the three Numerosity x Trial combinations (numerosity 2. p = 098, numerosity 3: p = 037; and numerosity 4· p = 045) It is clear that all of the numerosities contributed to the infants looking longer at novel than at old numerosities

Table 4 *Mean Number of Habituation Trials to Criterion for Age (5, 13 months) and Numerosity (2, 3, and 4)*

	Numerosity		
Age	2	3	4
5 months	8 4	9 6	9 1
13 months	13 4	11 0	16 0

To test the effect of homogeneous versus heterogeneous shapes on numerosity perception, we compared the proportion scores from this experiment with the proportion scores from the previous experiment. Separate MANOVAS were conducted on the proportion scores at 5 and 13 months of age, with experiment (homogeneous vs. heterogeneous shape), type of novel numerosity (x-1 or $x + 1$), numerosity (2, 3, and 4) as between-subjects factors and trial (old and novel) as within-subjects factor. At 5 months of age, the MANOVA yielded a marginal main effect of trial, F (1, 50) = 3.79, p = .057, which was qualified by a significant Experiment x Numerosity x Trial interaction, F (2, 49) = 5.59, p < .01. This result indicates that discrimination between old and novel numerosities was different for the numerosities with homogeneous versus heterogeneous figures. An inspection of the mean proportion scores suggests that especially numerosity 2 contributed to this effect. At 13 months of age, the MANOVA yielded only a significant main effect of trial, F (1, 50) = 12.19, p < .001. This suggests no effect of heterogeneity of shape for the numerosities that were discriminated.

To determine whether the different displays representing the numerosities 2, 3, and 4 were of equal interest and difficulty to infants of 5 and 13 months of age, various MANOVAS were performed on the measurements in the habituation phase with age (5 and 13 months) and type of novel numerosity (x-1 or x+1) as between-subjects factors and numerosity (x = 2, 3, and 4) as a within-subjects factor. A MANOVA on the total fixation time for the first three trials revealed a reliable main effect of age, F (1,44) = 16.04, p < .001. This indicates that across the different numerosities, the older infants looked less long at the initial numerosity presentations than the younger infants and, thus, may have been less interested in the displays.

We also investigated whether difficulty of habituation as measured by the number of habituation trials decreased with age. A MANOVA on the number of habituation trials to criterion yielded a significant effect of age, F (1,44) = 16.04, p < .001. The older infants required more trials to reach habituation criterion, but this effect was qualified by a significant Age x Numerosity interaction, F (2,43) = 5.23, p < .01 (see Table 4). This indicates that the increase in the number of habituation trials with age depended on the numerosity. This result is most likely an artifact of the small amount of attention that the older infants paid on the first three trials at 13 months of age, which obviously made it harder to reach habituation criterion. A MANOVA on the total looking time to criterion yielded no significant effects.

Discussion

Our results show 5- and 13-month-old infants to perceive the numerosity of small collections of independently moving elements even when shapes and sizes of the elements vary considerably. This extends our previous findings (van Loosbroek & Smitsman, 1990) and gives confidence in the robustness of infants' numerosity perception skills. It also supports the hypothesis that numerosity perception in infancy involves the pickup of information about unity. For 13-month-old infants, the results of the present study clearly confirm the results of the previous study in which the same motion displays were used but with homogeneously shaped figures. For the 5-month-old infants, the results also confirm our previous results in that numerosity perception is shown to be present at this age. In contrast to our previous study, the results of the present study showed discrimination between numerosities was to depend on the particular numerosity.

With regard to the heterogeneity of the elements, we found 13-month-old infants to perceive numerosity and the heterogeneity of shape to not affect this perception. The 5-month-old infants also perceived the numerosity of heterogeneous elements at 5 months of age, but this perception appeared to be confined to fewer numerosities than when the elements were homogeneous. These findings are intriguing because they deviate from the findings of previous numerosity studies involving collections of either moving or static elements. In interpreting these findings, we should keep in mind that more evidence is needed. If we nevertheless assume the absence of numerosity perception for numerosity 2 to be due to heterogeneity of shape, this is only partially consistent with a categorization hypothesis. Categorization requires the exploration of similarities and differences. Enhancing the dissimilarities within a collection by making the shapes of the elements heterogeneous should hamper the perception of the similarities across the elements, and, consequently, the perception of numerosity. In accordance with this hypothesis, 5-month-old infants were less able to perceive numerosity for heterogeneous than for homogeneous collections (e.g., Klahr, 1984a). Our finding that 5-month-old infants perceived the larger numerosity of 3 but not the smaller numerosity of 2 when the collections were heterogeneous is remarkable in this light, and does not directly follow from the categorization hypothesis. The similarities in the performance of 13-month-old infants with heterogeneous elements (the present study) and homogeneous elements (the previous study) is less remarkable in this light. By the age of 13 months, infants' abstraction may be sufficiently developed to enable them to perceive similarities between the elements in a collection even when there are clear dissimilarities.

Why 5-month-old infants perceived numerosity 3 but not numerosity 2 when the collections were heterogeneous still needs to be explained. A plausible explanation is the effect of heterogeneity on infant attention and visual exploration. The shapes of elements typically entail information that differentiates them from other elements and particularly especially when the differences in the shapes are as salient as in the present study. By 5 months of age, infants visual acuity has been sufficiently developed to scan the outline of shapes (Dobson & Teller, 1978). Although information about shape of an element is not needed for discrimination of the unity of the element, and may therefore not be needed for the perception of numerosity, it seems reasonable to assume that differences in the shapes of elements will afford visual exploration of the contours of these figures. Young infants may, however, have problems integrating their exploration of the shape of elements in motion with attention to the entire collection. That is, 5-month-old infants are perhaps less able than older infants to explore an individual element without losing sight of the other elements in the collection. Losing sight of the collection will obviously interfere with the perception of numerosity as the infants have to keep track of the elements in a collection in order to perceive its numerosity.

The perception of the larger numerosity 3 by 5-month-olds and not the smaller numerosity 2 may be due to the more detailed exploration of the shapes for only the smaller numerosity. In order to analyze an element's shape, the infant must keep track of the element across space and time. This may be relatively easy with only two elements and relatively few occlusions. With three elements and many more occlusions, the time that contours are partly concealed and move closely together greatly increases. Keeping track of the shape of a single element will be more difficult and attending to the collection of elements will thus be facilitated. If this hypothesis is correct, numerosity 3 was perceived by the 5-month-old infants, not because of their exploration of the similarities and differences within the collection, but because of their failure to do so. In other words, categorization may not be needed to perceive the numerosity of a collection.

Future research should help determine whether heterogeneity of shape is only one of the spatiotemporal properties of the elements in a collection that may interfere with the perception of their numerosity. Our hypothesis more generally implies that any property that enhances the distinctiveness of the elements in a collection may interfere with the systematic exploration of the elements, particularly at the age of about 5 months. Exploration of the collection may also be inhibited by properties that go beyond the individual elements, such as movement patterns. In this light, the findings from the present study are consistent with the findings from an earlier unpublished study with 5-month-old infants (van

Loosbroek & Smitsman, 1989). In that study, pattern relations such as parallel moving elements were present and numerosity was not perceived.

The present results clearly differ from those showing 5-month-old infants to be capable of perceiving the numerosity of small collections of static heterogeneous elements (Curtis & Strauss, 1983; Starkey et al., 1990; Strauss & Curtis, 1981). These contrasting results cast further doubt on the conceptualization of the perception of numerosity in terms of categorization. Why should categorization lead to numerosity perception in the case of both homogeneous and heterogeneous stationary elements and in the case of homogeneous but not of heterogeneous moving elements? In line with the present hypothesis, we suggest that the stationary position of the elements made it possible for infants to explore the shapes of single elements while not losing sight of the collection. Moving elements made it difficult for infants to keep track and explore the shapes of single elements as well as perceive the numerosity of a collection of heterogeneous moving elements in particular.

Taken together, these findings suggest that development of numerosity is still unstable at the age of 5 months. This ability appears to be easily affected by variations in the presentation of small collections of elements. The instability concerns the process of how elements are accrued to numerosity. We view the perception of numerosity as an active search for information (Smitsman, 1994). When infants look at a collection of elements and visually explore the display, the spatiotemporal properties of the relevant elements will presumably constraint the exploratory activities of the infants and thus the information they pick up. An important constraint on a system scanning a display for information about unity is the number of elements for which such information must be obtained. When development of numerosity perception is complete, these exploratory activities will presumably differ more or less systematically for different numerosities. When numerosity perception is still unstable and attention is not well controlled, exploration may focus on such properties as shape or pattern of motion. Attention may be easily diverted to the various spatiotemporal properties of the relevant elements. For a more complete understanding of the development of numerosity perception, we need to investigate infants' exploration of small collections and the properties that affect this exploration in greater detail.

4 Study III: Perception of Numerical Addition in Infancy

We investigated whether infants keep track of the numerosity of a collection of figures that increases by addition of another figure. Addition was displayed as a figure that came into view from the side of a TV screen and was added to figure(s) already present. For an addition event (e.g., 1+1), the numerosities over time are the initial or augend collection (i.e., 1), the addend or the numerosity of figures that are added (i.e., 1), and, finally, the sum or the collection of figures that results after the addition (i.e., 2) The results showed that infants start discriminating numerosities in an addition somewhere between 8 and 14 months of age But even at 14 months of age, not all numerosities during addition were discriminated At this age, infants perceived that no addend as well as a larger addend than the old addend (+1) occurred Infants still did not perceive that an addition occurred with a smaller augend collection.

Introduction

The development of children's numerical abilities in the first two years of life has received increasing attention over the past two decades. Some studies of numerical abilities in infancy focused on visual perception of numerosity as an invariant property of collections of elements. Overall, these studies demonstrated that infants from at least 5 months of age were able to perceive numerosities ranging from about 1 to 4 elements (e.g., Chapters 2, 3; Starkey & Cooper, 1980; Strauss & Curtis, 1981). The general method used in these studies was that infants were habituated first to displays of, for example, 2 elements. During habituation numerosity remained constant, whereas other properties, such as configuration and shape of elements, were varied. On test trials, a novel numerosity of, for example, 3 elements was presented that also remained constant over time. Recovery of attention indicated that infants discriminated between the two different numerosities.

By contrasting two different numerosities, these studies demonstrated that infants were able to perceive that numerosity had been changed. However, these studies did not demonstrate whether infants perceive an increase in size of a collection by adding a new element to the collection, and the size that results from adding. Recently, this question was addressed in a series of studies (e.g., Simon, Hespos, & Rochat, 1995; Starkey, 1992; Wynn, 1992a). In the present study, we also addressed this question by investigating infant's ability to discriminate the different numerosities that constitute an addition event. An addition event takes place when an initial collection of elements increases by the addition of one or more elements.

An addition event is composed of the following three different numerosities over time: the augend collection or the initial numerosity, the addend or the numerosity added, and the sum as the resulting numerosity. Consider, for example, the event of two dogs chasing one another on a field. Appearance of another dog into the scene (i.e., the addend) joining the two dogs (i.e., the augend), increases the collection with one and changes the number of dogs into three (i.e., the sum). To perceive the numerosities that are available during the course of the event, infants have to sample unity information orderly. They have to keep track of the elements for which this information is available, but also of the change that happens when new elements are added. Their ability to discriminate small numerosities allows infants to detect the numerosities that subsequently appear within addition events, provided the numerosities are within the range of numerosities they can perceive. However, to perceive these numerosities as different components of an addition event, infants need to be aware of the way these numerosities are embedded within the event. We investigated whether infants perceive the numerosities that are embedded within addition events. Specifically, we investigated infants' ability to discriminate numerosities that constitute an addition. We presented an addition event to infants and assessed whether they discriminated the size of the augend collection, the size of the addend, and the adding itself.

To date, it is not clear to what extent infants' keep track of the numerosities that are involved in addition. Earlier studies focused on infants' perception of the numerical outcome of an addition event. Thus, they only provided indirect evidence that infants distinguish numerosities over the course of an addition event. Part of these studies (Sophian & Adams,1987; Starkey, 1983, 1992) involved a paradigm in which infants had to actively perform manual search behavior. For example, in the studies of Starkey, infants first looked at an addition of objects into a container. Following the addition, the infants had to take the number of objects out of the container. The number of objects they took out was evidence as to whether they understood how many objects had been put into the container. Starkey found that children of about 2 years and older know precisely how many objects there are after they have observed additions to or deletions of one object from a hidden, but known collection of objects provided that the number of this collection was small. Sophian and Adams (1987) demonstrated that infants of 14 months and older perceive that addition changes the numerosity of a collection. But only infants of 24 months and older performed correctly most of the time. These studies did not make clear, however, what infants detect from additions before 14 months of age. To study early understanding of addition, a perceptual task is more appropriate than a manual search task, because, supposedly manual exploratory actions are less differentiated and less well controlled than visual exploration before 14 months. Two recent studies used a perceptual task to investigate perception of the numerical outcome of addition.

In studies of both Simon et al. (1995) and Wynn (1992a), 5-month-old infants were habituated to an addition event for which they observed the augend and addend collection consecutively, but never simultaneously. Thus, they could not observe the resulting sum collection. On the test trials, infants looked at a sum numerosity of a collection that was either consistent or inconsistent with the transformation that had taken place. In both studies, they found that infants of 5 months of age looked longer at the incorrect sum collection than at the correct sum collection. This finding indicates that they anticipated the numerical outcome correctly. Wynn explained her results by suggesting that "...infants can compute the results of simple arithmetical operations" (p. 750). This suggestion implies that infants of 5 months of age who anticipate the outcome of an addition correctly must also be aware of the size of the augend as well as the size of the addend in an addition event.

We further investigated the hypothesis that infants are aware of the size of the augend as well as the size of the addend in an addition event. We established infants' visual perception of addition by displaying addition events to them in which an additional element visibly joins a collection of elements already in sight. We generally used a similar design, display, and procedure as in our previous numerosity studies (chapters 3 and 4). Infants habituated to an addition that was analogous to the example of the playing dogs. First, two elements (i.e., augend) moved on a TV screen. After a while a new element (i.e., addend) came into sight on the screen and intermingled with the other two elements, resulting in three elements on the screen (i.e., sum). The elements we displayed consisted of two-dimensional, textured figures that were moving independently and constantly. The way an element comes into sight may affect the age at which infants demonstrate the ability to perceive addition of numerosity. We chose disocclusion from the side of a screen as the transformation to display addition of a novel element. This transformation was shown by progressively bringing a textured figure into sight from behind the occluding edge at the side of the screen. Infants of 5 months of age are able to detect information for disocclusion (e.g., Craton & Yonas, 1988; Granrud, Yonas, Smith, Arterberry, Glicksmann, & Sorkness, 1984).

The question whether infants can discriminate components of addition events was addressed in two experiments. Infants were always habituated to an addition of one element (symbolically: e.g., *2+1*). In the test phase, we presented three variations of the addition in the habituation phase (e.g., *2+1*) that consisted of addition with either a smaller augend, no adding or a larger addend. The smaller augend collection was one less than in the habituation phase. For example, instead of an augend collection of two elements in an addition (i.e., *2+1*), the augend collection involved one element only (i.e., *1+1*). When adding itself was varied, no addition of an element to two elements, but only the sum collection of the (*2+1*)-addition was presented (i.e., 3). As a third variation, instead of an addend of one element to a collection of two elements (i.e., *2+1*), a greater addend was shown for the same augend collection as displayed in the habituation phase (i.e., *2+2*).

Specific patterns of results for these conditions may reveal the numerical components that infants notice from an addition event. If infants only attend to the addend and not to the initial elements in the augend collection, they will discriminate between addition events differing in addend (i.e., (*2+1*) and (*3*), and (*2+1*) and (*2+2*), respectively) and will not discriminate between addition events differing in size of the augend (i.e., (*2+1*) and (*1+1*), respectively). If infants only attend to the initial elements in the augend collection and do not attend to the addend collection (i.e., +1), they will not discriminate between (*2+1*) and (*2+2*), but will discriminate between (*2+1*) and (*1+1*). Finally, if infants attend only to the sum collection and do not notice that an addition takes place, they will not discriminate between (*2+1*) and (*3*), but will discriminate between (*2+1*) and (*1+1*) on the one hand, and (*2+1*) and (*2+2*), on the other hand, respectively.

Based on previous findings which indicate that infants not only perceive small numerosities, but also perceive the outcome of additions, we hypothesized that infants differentiate the numerosities involved in an addition event. To test this hypothesis, we, first, investigated perception of addition in an experiment with infants of 5 months of age, and in a subsequent experiment with infants of 8 and 14 months of age using a somewhat modified procedure. In the first experiment, the augend collection involved the numerosities 1 and 2. In the second experiment, the augend collection involved only the numerosity 2. Moreover, the displayed elements moved at trajectories that differed from the first experiment.

Experiment 1

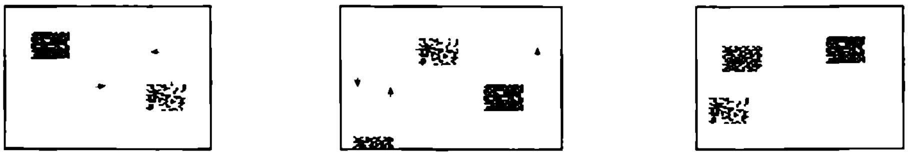
In the present study, discrimination of addition components was investigated for two different augend collections and involved the numerosities 1 and 2, because previous studies suggested that numerosity perception may be unstable at 5 months of age and may depend on the size of the collection (Chapters 2 and 3). It is, thus, possible that perception of addition is also not very robust and, perhaps, dependent on the size of the collection.

Method

Subjects. Sixty infants of 5 and 6 months of age participated in this study (mean age = 23 weeks). An additional 14 infants had participated but were excluded from our analyses because they showed fussiness or sleep at two sessions (n = 11), or their parents refused to participate any longer (n = 3). Names and addresses of infants were obtained from the municipal government in Nijmegen. Infants were recruited without any selection and infants participated after informed consent by the parents. Parents were paid a small amount of money for their participation.

Procedure. The infants were tested individually in two separate, randomly ordered sessions. The two sessions were spread across an interval of seven working days. Sessions were never on the same day and, normally, not on two consecutive days. During all sessions, infants were seated on their parents' or caretakers' lap whom were instructed not to look at the display. The vast majority of the parents did not look at the display at all whereas others looked once or twice and very briefly.

Infants looked at an addition event on a 16 x 24 cm black-and-white TV monitor. Depending on the session, the addition event consisted of 1 or 2 elements already present (augend collection) to which 1 element was added (i.e., addend = 1). We label these addition events as (*1+1*) and (*2+1*), respectively. These addition events were displayed in the following way (see Figure 4).



phase 1 at 0 s phase 2 at 3 s phase 3 at 7.6 s

Figure 4. Schematic representation of three phases in addition event (2+1).

First, a number (i.e., 1 or 2) of moving elements was shown. Secondly, after approximately 2 s, a new element came into view by a gradual disocclusion of the contours and inner surface of an element appearing from one of the sides of the TV monitor. Third, the new element mixed with the other element(s). The addition part of the event took approximately 5 s. The duration of the complete event was always 7.6 s. After presentation of the complete event an empty screen was visible for approximately 1 s. Then the event was repeated with the same figures, movements and gray-colors. Figures were 3.3. x 2.3 cm large and consisted of matrices of 16 x 16 pixels randomly filled (see Figure 1). The movements progressed at a constant rate along curvilinear trajectories at varying orientations. In these movements, figures could partly and temporarily occlude other figures. Movements of elements of the augend collection were randomly chosen out of eleven possible trajectories. Movements of the elements that were added (i.e., the addend collection) were randomly chosen out of a different set of eleven trajectories. Movement trajectories of elements that were added varied in time of entry and location of entry from the sides of the TV monitor, as well as distance traversed. Location of entry occurred at varying points on either the top, down or right side of the TV monitor. There were 17 gray-colors and they were all translucent. Figures, movement trajectories, number and degree of occlusions, and gray-colors were randomly varied for every trial. A computer controlled the display on the monitor and the procedure.

The procedure used was an infant-controlled habituation of visual looking time task controlled by the computer and consisted of a habituation and a test phase. The beginning of each trial was signaled by a tone. A trial consisted of a repeated presentation of an addition event. Because it seemed important that infants had the opportunity to look at the whole event at least once during a trial, we developed the following procedure. A trial was ended when either one of the two following conditions were met. The infant had looked away for at least 2 s continuously, provided that the end of this 2 s period occurred later than the first complete presentation of the addition event (i.e., after 7.6 s), or the infant had a total of 10 fixations. The first three trials of the habituation phase were used to compute the habituation criterion. The criterion was set at half of the mean fixation time on these first three trials.

The habituation phase ended and the test phase started if either one of the two following criteria were met. The habituation criterion was reached on three consecutive trials or after a randomly determined number of trials that could range from 16 to 23. The test phase in this study consisted of four trials: two old (O) trials and two novel (N) trials. On O trials, the event of the habituation phase was again presented. On N trials, a novel event was presented.

Infants were randomly assigned to one of three conditions that varied with respect to the event shown in the test phase. . Depending on which of the three conditions the child was assigned to, the novel event consisted of one of the three following conditions. *Condition 1*: The sum of the addition in the habituation phase was displayed, that is, no increase in numerosity was involved. Depending on the session the sum was 2 (based on *1+1*) or 3 (based on *2+1*), respectively. *Condition 2*: An addition with the same addend (+*1*) as in the habituation phase but to a novel augend collection that was always one less than in the habituation phase, that is, 0 or 1, respectively. The novel event was then either (*0+1*) or (*1+1*). *Condition 3*: An addition was displayed with a larger addend (+*2*) than in the habituation phase but to the same augend collection (1 or 2, respectively). The novel event was thus either (*1+2*) or (*2+2*). The test phase consisted of O and N trials in two different orders: O-O-N-N or N-N-O-O. These two orders were randomly varied across sessions.

Not more than one session per child could be rerun if a session had to be stopped because an infant was fuzzy or sleepy. Of all sessions, 9% was rerun.

Results and Discussion

We followed the analyses of our previous studies and always compared combined fixation times for both N trials with the combined fixation times of the two preceding trials. That is, for the O-O-N-N order, these trials were the two preceding O trials in the test phase. For the N-N-O-O order, however, these trials were the last two trials in the habituation phase rather than the two subsequent O trials in the test phase. In case of the N-N-O-O order, we used a statistical procedure to estimate the spontaneous recovery in fixation times of the N trials compared with that of the two preceding (i.e., the last two habituation) trials. The spontaneous recovery in fixation time that was found between the last two habituation trials and the two subsequent O trials in the O-O-N-N order was added to that of the last two habituation trials of the N-N-O-O order. The estimated recovery score was computed across conditions.

To homogenize variances, we transformed visual fixation times in the above comparisons to proportion scores by dividing both the fixation times on the last two O trials and the fixation times on the two N trials by two thirds of the combined fixation times on the three trials preceding the test phase. A MANOVA was performed on proportion scores with type of novel event (sum, smaller augend collection, larger addend) as the between-subjects factor and numerosity (1 and 2), and trial (O and N trials) as repeated measures. The analysis revealed no differences across or within conditions (see Table 5 for the means). Overall, infants did not look longer on novel than on old trials for the numerosities presented for any novel event. Further exploration of the proportion scores by adding factors did not reveal significant effects either. Added factors were whether the old as well as the novel trials were the first or second old or novel trial presented, or whether infants attended the first or second session.

Table 5 *Combined Transformed Mean Fixation Time Scores for Type of Novel Event (sum, larger addend, smaller augend), Size of Augend Collection (1, 2), and Trial (old vs. novel)*

		Type of Novel Event		
Numerosity	Trial	Sum	Larger Addend	Smaller Augend
1	Old	1.321 (1.40)	1.300 (0.84)	1.186 (0.76)
	Novel	1.541 (1.35)	1.226 (0.83)	1.347 (0.90)
2	Old	1.605 (1.73)	1.018 (0.43)	1.390 (1.20)
	Novel	1.481 (1.56)	1.196 (0.75)	1.575 (2.14)

Note The number of infants in each cell is 20. Standard deviations are between brackets

Although we found no effects for this group of infants, effects in the transition stage before development is completed may be dependent on the developmental stage at which individual infants function for a particular skill. Baillargeon (1987) and Spelke, Katz, Purcell, Ehrlich and Breinlinger (1994) found some evidence for the hypothesis, that before development reaches a stable state, infants who habituate more rapidly also seem to have a greater preference for novel stimuli. Only in the transition stage, early developers compared to late developers showed a significant correlation between short total looking time across habituation trials and relatively larger looking times to novel than to old stimuli on test trials. It is assumed that before as well as after this transition stage, no such relation exists. In a test of whether the present 5-month-olds were in a transition stage concerning their perception of addition, a covariance analysis on proportion scores was performed with total looking time to criterion as a covariate. This analysis did not reveal any evidence of a transition stage in which some individual infants were more able to perceive addition events than others.

We also analysed whether the addition events presented differed among the infants in preference or complexity as may be revealed by differences in looking times on the first trial in the habituation phase or across habituation trials. A *t*-test of the looking times on the first trial revealed that infants looked longer at the event of (*2+1*) than at the event of (*1+1*). Apparently, the infants in the larger addition condition (*2+1*) needed more time to get familiar with the event.

In sum, the results of this study did not provide support for the hypothesis that 5-month-old infants differentiate addition events from non-addition events, or differentiate addition events with respect to the size of the augend, or addend collection. Although negative results are difficult to interpret, the relatively low variance of looking times in the test phase (see Table 5) compared to the high variances at this age in our previous numerosity studies (e.g., see Table 1) suggests that perception of addition is not even beginning to develop at this age. Because infants can perceive small numerosities at this age (chapters 2 and 3), it appears that the structure of addition is problematic. Assuming that 5-month-old infants did not perceive these events, the findings underline the importance of task context for numerosity discrimination by 5-month-old infants. In this experiment infants did neither perceive a change in augend, nor a change in addend, and consequently also not a change in sum. Even the way this sum was realized remained unnoticed because infants did not discriminate between two different events that had the same numerosity at the end such as when they looked at (1+1) and (2).

A possible explanation for the absence of effects may be that the visual system needs some time to set up and complete a particular organization of activities that is attuned to the event infants are looking at. Addition of a new element may have hindered infants to evolve the proper organization of activities that allows perception of the numerosities displayed. The longer looking times for the larger augend addition (*2+1*) suggests that the presence of more elements increases the time to set up and complete visual exploration. This is consistent with the hypothesis that the visual system needs time to evolve the proper organization for the exploratory activities. It probably takes more time to do this in infancy than in adulthood.

Experiment 2

Because we found no evidence for the assumption that 5-month-old infants differentiate between the components of addition events (i.e., the augend collection, the adding itself, or the size of the adding) we extended our investigation to two older age groups, that is, to 8- and 14-month-old infants, respectively. Furthermore, we introduced a few changes in the procedure to enhance perception of addition events for the investigated age groups. First, infants were habituated to addition events involving the augend collection of two elements only (i.e., *2+1*). A second change concerned the type of trajectories. In Experiment 2 linear motion trajectories were used, whereas curvilinear motion trajectories had been used in the previous experiment. Elements following linear trajectories traversed somewhat greater distances on the screen within the same period of time than elements following curvilinear trajectories. This variation gave a little more intermingling of elements of the augend collections and elements that were added. This experiment also differed with the first experiment in that movements were somewhat slower, resulting in an addition event that extended longer over time than in the first experiment.

Finally, this experiment required fewer infants than the first experiment. The three conditions of the test phase (i.e., novel augend, no adding or larger addend) were no longer attributed to separate groups of infants but, instead, were randomly varied within infants. For the rest, both experiments were comparable and involved the same methods concerning subjects, procedure, design, and analyses

Method

Subjects. Two age groups of infants (each n = 12), one of 8- to 9-month-olds (mean age = 38.2 weeks) and the other of 14- to 15-month-olds (mean age = 64.4 weeks) were investigated. An additional two infants from the former age group were excluded from the analyses because they were fretful or drowsy at two of the three sessions.

Procedure. Infants were tested individually in three separate sessions randomly ordered across seven days. In each session, infants looked at an event that consisted of the addition of one element to two elements already in sight (symbolically: *2+1*). This addition event looked similar to the addition event in the previous experiment (see Figure 4) but differed in timing and type of trajectory. First, 2 moving elements were shown. After approximately 2.5 s another element came into view by disocclusion from one of the sides of the monitor and mixed with the other two elements. The addition part of the event took approximately 7.0 s and the whole event took always 10.5 s. After each complete event an empty screen was visible for approximately 1 s. Then the whole event was repeated with the same figures, movements and gray-colors.

Instead of curvilinear trajectories, movements of elements initially present (i.e., the augend collection) and the element added progressed at the same, constant rate along linear trajectories at horizontal, vertical or diagonal orientations on the monitor. Linear movements were used to ensure maximum distance traversed within a limited time and, hence, greater intermingling of elements. Movements could consist of reversals of moving direction but not of a change in orientation. Reversal of movement direction could happen once or several times at different phases of the trajectories while keeping the movement's horizontal, vertical, or diagonal orientation. Precaution was taken that no specific patterns across moving elements arose, as a result of parallel movement or reversing the direction at the same time (see van Loosbroek & Smitsman, 1989).

The addition event presented in the habituation phase was the same for all infants: (*2+1*). On O trials in the test phase, the addition event was again presented (i.e., *2+1*). On N trials, infants looked at a novel event. Novel events consisted of the same three variations as in the previous experiment. These variations were the following. *Condition 1:* the sum of the addition in the habituation phase (i.e., *3*), that is, no change of numerosity was involved. *Condition 2*: an addition with the same addend (*+1*) as in the habituation phase but to a smaller augend collection (i.e., *1+1*). *Condition 3*: an addition with a larger addend (*+2*) than in the habituation phase but to the same augend collection (i.e., *2+2*). These three conditions were randomly varied across sessions within infants.

Results and Discussion

First, we inspected the mean looking times of the last two habituation trials before the test phase at each age. Mean looking times on both types of trials were 10.2 s (SD = 9.6) and 10.6 s (SD = 15.3) at 8 months of age and 9.9 s (SD = 8.1) and 9.7 s (SD = 8.1) at 14 months of age, respectively. Comparison of these mean looking times and duration of the addition event (i.e., 10.5 s) suggests that infants on average had the opportunity to observe at least one complete addition event.

Second, looking times were transformed to proportion scores in the same way as in the first experiment. A 2 x 3 x 2 MANOVA was performed on the proportion scores with the between-subject factor age (8 and 14 months), and the repeated measurements type of new event (sum, smaller augend, greater addend) and trial (O and N). Only the main effect of trial was significant, F (1,22) = 6.93, $p < .025$, suggesting that generally infants looked longer at the novel than at the old addition event. Pre-planned comparisons of the trial effect (a = .01) for each of the six combinations of type of new event and age (see Table 6) showed only marginal significant effects for 14-month-olds when no addition but the sum was presented ($p < .051$), and when a larger addition was presented ($p < .075$). Although no interaction of Trial x Age was found, the results seem to suggest that 14-month-old infants but not 8-month-old infants may differentiate some components of addition events.

Table 6. *Combined Transformed Mean Fixation Time Scores for Age (8, 14 months), Type of Novel Event (sum, larger addition, smaller augend), and Trial (old, novel)*

Age	Trial	Type of Novel Event: Sum (3)	Larger Addend	Smaller Augend
8 months	old	1.480	1.169	0.952
		(0.81)	(0.57)	(0.40)
	novel	1.478	1.781	2.519
		(1.39)	(1.60)	(3.75)
14 months	old	1.233	0.968	1.327
		(0.76)	(0.28)	(0.83)
	novel	2.260	1.595	1.640
		(2.63)	(1.47)	(0.94)

Note. The number of infants in each cell is 12. Standard deviations are between brackets.

Despite the marginal significance of the effects, we take the results as evidence for perception of addition at 14 months of age, because other studies also suggest that infants of this age can perceive specific, though perhaps not all characteristics of an addition event by 14 months of age (Baillargeon, Miller, & Constantino cited in Wynn, 1992c; Simon et al., 1995; Sophian & Adams, 1988; Wynn, 1992b). Our results suggested that 14-month-old infants perceived two specific characteristics of an addition event. First, they perceived when no addition occurred, because they discriminated between the addition (*2+1*) and no addition (*3*). Second, they perceived when a larger addition occurred, because they discriminated between (*2+1*) and (*2+2*). However, our results did not provide evidence for the assumption that infants of 14 months of age perceived that the addition involved a smaller augend collection. After all, infants did not discriminate between the additions (*2+1*) and (*1+1*).

Given the marginal significance, we further explored the results but these analyses did not change this conclusion. Specifically, we carried out the same analyses as above but without combining either the two old or novel trials (i.e., 1st O or N trial, 2nd O or N trial). Instead, order of trial (first and second) was added as a factor. No significant effects were found. Then, order of session (first, second, and third) was added as an extra factor in the analysis, but it did not show any relation with infants' discrimination of old versus novel addition events.

As in experiment 1, we analysed whether the proportion scores across ages were in accordance with the developmental trend suggested by Baillargeon (1987) and Spelke et al. (1994). Only in a transition phase, higher looking times for novel events may be inversely related to the height of looking times across habituation trials. Before development would have started, or after development would be complete no such a relation between habituation and test trials would exist. The results of a covariance analysis with looking times across habituation trials as a covariate and proportion scores as the dependent variable did not reveal that across conditions higher looking times on novel versus old trials was related to looking times across habituation trials.

A further set of analyses was carried out on measures of the habituation phase with the between-subject factor age (8 and 14 months) and the repeated measurements factor session (first, second, third) to investigate possible effects of interest and difficulty. A MANOVA of looking times on the first trial as well as of total looking times across all trials in the habituation phase yielded a main effect of session, $F(2,21)= 4.42$, $p < .025$, and $F(2,21)= 6.66$, $p < .01$, respectively. An inspection of the means showed in general that both variables exhibit a trend that on later sessions attention to the addition transformation (*2+1*) at the first trial or across habituation trials is less than on earlier sessions. The lower attention at later sessions may have had a negative effect on the general difference in looking times between O and N trials, because low attention is not a very good condition to ensure noticing of differences within a complex event.

In conclusion, perception of the numerosities involved in addition events appears to develop between 8 and 14 months of age. This development may not have been completed at 14 months of age, because still not all components in the addition event were differentiated at that age. Specifically, infants seemed not to discriminate between the smaller augend collections in the addition (*2+1*) and in the addition (*1+1*).

General Discussion

The two experiments indicate that perception of numerical addition develops in infancy between the ages of 8 and 14 months of age. Infants of 5-months-old do not yet distinguish numerical components in addition events. Compared to discrimination of numerosity, differentiation of numerosities that compose addition events appears to be a relatively late development. Infants of 5 months of age perceive numerosity (e.g., Chapters 2 and 3; Starkey & Cooper, 1980; Strauss & Curtis, 1981), but do not properly distinguish the numerosity of the augend, addend and sum collections during the course of an addition event.

Differentiation of the components of an addition event also appears to be a relatively late development compared to anticipation of the numerical outcome of a small addition that has already been found at 5 months of age (Simon et al., 1995; Wynn, 1992a). This finding is surprising if one assumes that knowledge of the numerical outcome of an addition implies knowledge of both the augend and addend. It is even more surprising that infants at the later age of 14 months still did not discriminate between addition events differing in augend (i.e., *2+1* versus *1+1*). An absence of discrimination between these addition events suggests that not only infants did not perceive the size of the augend collection to which an element is added, They also did not seem to perceive the sum of the addition. Although our results need replication as well as an extension to other numerosities, they suggest that infants between 8 and 14 months of age start differentiating numerosities that are available over time in an addition event, but this ability is not complete at 14 months. Infants at 14 months of age seem to notice consistently only when no addition or a larger addition took place.

Our findings about infants' visual perception of an addition event are in line with findings of other studies of numerical addition that differ in methodology and design (see e.g., Sophian & Adams, 1988; Starkey, 1983, 1992). These studies suggest that awareness of an addition event certainly is not complete by the age of about 14 months, and continues to develop until the infant is older than two years of age. In an unpublished study (van Loosbroek & Smitsman, in preparation), we used a similar display and procedure as in the present study and also did not obtain evidence that awareness of numerical addition is present in infants younger than 14 months of age. Infants of 11 months of age did not discriminate between an addition event of a type as in the present study, that is, involving an augend collection (x) already in sight to which an element was added by disocclusion (i.e., $x+1$), and an event in which numerosity remained constant over time for any augend presented (i.e., involving only a collection of x elements; x = 1, 2, or 3 elements).

It is not fully clear how to interpret infants' behavior in light of all these findings. For example, infants' lack of discrimination of the augend collection at 14 months of age, but clear discrimination of the addition transformation may be due to the way we displayed addition. The appearance of an element from the side of the screen may have attracted infants' attention. As a consequence they lost track of the elements already in sight. The difficulty of addition events for infants may, however, not or only partly be due to the particular transformation by which we displayed addition. Infants lack of discrimination may point to more basic limitations in numerosity perception at that age. Because the additional element appeared soon after infants had started sampling unity information of the augend collection over time, the appearance may have disturbed this sampling process. It may also have disturbed the organization that is needed to keep track of the numerosity displayed. Comparable disturbing effects have been found in verbal counting. Observations on verbal counting (see Fuson, 1988) show that young children have difficulties adapting the ongoing counting to mistakes they make, or to changes in the number of elements. Likewise, the addition transformation may complicate the search for unity information, and, especially, the monitoring of the number of elements for which this information is available over time. A differentiated perception of the structure of the event that changes numerosity may require more flexible and stable organizations of perceptual activities than infants younger than 14 months of age have developed.

Although a fully differentiated perception of addition events was not present, 14-month-old infants noticed important properties of an addition event. They focused on the component of the addition event that specified the increase in numerosity. Attending to the addition is, of course, a very effective strategy for perceiving changes in numerosity. The infants did not appear to rely on less effective strategies as in attending only to the numerosity in, for example, the beginning phase of the addition event when the augend collection was shown. With this strategy, the increase in numerosity would remain unnoticed. If infants only attended to the initial phase of the addition event, they should have discriminated between the differently sized augend collections (i.e., *2+1* versus *1+1*, and *2+1* versus *3*). However, the smaller augend collection was the only component that never show a reliable effect for looking times, not even for infants of 14 months of age. Also, young infants of 5- and 8-months-of-age did not show a "recency" strategy in that they only attended to numerosities at the end of the addition event. In that case, they would have discriminated between the conditions in which the resulting sum collection was different (i.e., *2+1* versus *1+1*, and *2+1* versus *2+2*).

In general, the results of the present study make clear that perception of addition events may be conceived of as consisting of the same processes as perception of numerosity. The mere existence of differences in the age at which numerosity and changes in numerosity are perceived, does not necessarily imply that we need to invoke completely different processes to explain performance. There is abundant evidence in infancy research is showing examples of different designs and procedures leading to age differences for the same ability (e.g., Leslie, 1984 versus Oakes & Cohen, 1990; Baillargeon, 1986 versus Sitskoorn & Smitsman, 1995). In the same way, as perception of numerosity may vary across age, depending on the way collections are displayed (see Chapters 2 and 3), perception of numerical addition may also vary across age depending on the way addition events are displayed, or on the tasks that infants have to perform.

More specifically, however, the discrepant findings regarding perception of addition and anticipation of the outcome of addition events call into question why two events that both involve addition can be perceived so differently. Evidently, more research is needed. Further investigation of addition events may also clarify the nature of numerical development in infancy for other reasons. If infants perceive what happens to numerosity during an addition event, we have evidence that infants perceive the change the size of a collection (e.g., addition). We already know infants to perceive that numerosity remains constant under transformations that have no effect on the size of a collection of elements (e.g., change in pattern). Taken together these findings may show when infants discriminate among numerically relevant and numerically irrelevant numerosities. Discrimination between numerically relevant and numerically irrelevant transformations forms the basis of any numerical ability (Gelman & Gallistel, 1978; Piaget & Szeminska, 1941). In addition, it may clarify to what extent perception of ordinality is related to perception of an increase in numerosity through addition of a novel element. Although Wynn (1992a) assumes that infants of 5 months of age who can perceive addition, should have some knowledge of the ordering of numerosities, Cooper (1983) and Curtis and Strauss' (1983) results suggest that perception of ordinality starts developing not earlier than at the age of 14 months. This age is consistent with the onset of perception of addition as suggested by our results.

5 Study IV: Perception of the Outcome of Numerical Addition in Infancy[3]

We investigated whether 8- and 14 month-old infants anticipated the outcome of an addition The addition that was shown involved one object that was placed into sight and, subsequently, concealed by a container A second object was, then, shown and put into the container (i e , *1+1*) Only 14-month-old but not 8-month-old infants anticipated that the outcome of this addition would be two, and not one or three objects These results deviated from results of other studies on addition (*1+1*) To explain this, we suggested that perception of the unity and persistence of objects within a container might be problematic for younger infants, because the space occupied by the container includes the space occupied by the objects in the container

Introduction

Objects play an important role in the visual world of an infant. Objects are involved in all kinds of transformations. For example, objects are displaced and manipulated These transformations may have consequences for the number of objects present. Do infants perceive the number of

[3] Portions of this study have already been reported as Smitsman van Loosbroek, Arends & Stultiens (1987)

objects resulting from these transformations? This study investigated infants' pickup of information about the number of objects that changes due to manipulations. More specifically, we investigated whether infants perceive the outcome of numerical addition of one object to another object.

We already know that 5-month-old infants perceive an object as a persisting and distinct unit when this object is moved out of view and put behind a screen (Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985). Furthermore, recent research has shown that perceiving an object as a persisting and distinct unit when put out of view is not limited to the occurrence of just one object. Five-month-old infants correctly anticipated the outcome of manipulations for two objects. These manipulations involved, first, presentation of one object that was subsequently hidden by a screen. Following that, a second object was shown visibly to the child at the side of the screen and displaced behind the screen. In other words, the two objects were never in sight at the same time. Infants anticipated that only two objects could be present when the screen was away, and not one or three (Wynn, 1992a; Simon et al., 1995). Similarly, these infants also correctly anticipated the outcome of a deletion of one object from a group of two objects that had been in sight. Initially, two objects were shown and, subsequently, screened from view, and, then, the deletion was performed. As revealed by their looking times, infants expected one object only and were surprised (i.e., had longer looking times) when two or three objects appeared from behind the screen.

These findings are important for various reasons. First, the findings are convincing, because an exact replication of Wynn's study (1992a) by Simon et al. (1995) provided the same results. Second, the findings demonstrated infant's perception of small numerosities over time at a very early age. Moreover, they demonstrated infants' perception of numerical transformations, such as addition (i.e., in numerical symbols: *1+1*) and deletion (i.e., *2-1*), that change initial numerosities and result in novel numerosities. Because these findings concern perception of numerical transformations at such an early age, they may contribute a great deal to our understanding of early development of numerical perception. Additional findings may further clarify how infant's perception of numerical transformations and their outcome can be conceived. Therefore, we report the present study that replicated the above studies with a slightly different procedure, for the addition (*1+1*) only, and at later ages.

Wynn (1992a) presents a cognitive explanation for how infants anticipate the outcome of numerical transformations. Her interpretation of the findings is that 5-month-old infants can "compute the results of simple arithmetical operations" (p. 750), such as the addition (*1+1*), or the deletion (*2-1*). Essentially, she suggests that infants' visual reactions to displayed additions and deletions is the result of computing processes that operate on representations of the number of units available during these transformations. This view appears to be problematic, because it is not supported by the evidence so far. If perception of addition would involve computing processes, this implies discrimination of the augend of 1 (i.e., the numerosity of the initial collection of objects) and the addend of 1 (i.e., the numerosity of the objects added) in the addition (*1+1*). We found, however, no evidence (see Chapter 4) that 5-month-old infants are able to distinguish the augend and addend for the addition (*1+1*) in terms of augend and addend and discriminate this addition from additions involving a different augend or addend (e.g., *0+1* or *1+2*, or , respectively). Only between 8- and 14-months of age, infants start perceiving addition in terms of the addend involved.

Moreover, Wynn's cognitive view of addition appears to imply that task variation in general should have little effect on infants' perception of numerical transformations. What type of units are involved, or how addition occurs should not matter. Only the numerosity involved in the addition might matter (e.g., *1+1* or *2+1*) because this would affect the complexity of the computation processes. In other words, these processes may be affected by the size of the numerosities, but not by how the addition (*1+1*) is shown.

However, Thelen and Smith (1994) have argued that task variation is at the heart of early development of perception and cognition and may account for many age differences in what infants perceive. Their view is called the dynamical approach and it may help to explain how perception of numerical transformations emerges. According to this dynamical approach, knowledge emerges as the result of distinct internal processes that become coupled over time. In line with this approach, we suggest that perceiving the outcome of numerical transformations may be highly context-specific initially in development. In particular, infants may perceive additions differerently depending on the way they are shown. Different transformations, such as when addition involves the putting of objects behind a screen or in a container, may lead to different achievements in infants.

In our opinion, there is evidence that suggests that perception of the outcome of numerical transformations is dependent on the task that infants perform or on the context in which numerical transformations such as addition are presented. For example, Starkey (1992) investigated infants' understanding of the addition (*1+1*). Instead of using a preferential looking time task for assessing the visual preference for correct (2) versus incorrect (1, 3) outcomes of the addition (*1+1*) as Wynn (1992a) did, Starkey used a manual search task. Furthermore, the objects were put into a container and not behind a screen. In Starkey's study, the infants watched how an experimenter performed the addition (*1+1*) by putting two objects one after another into a container that concealed the objects from view. Infants had then to search manually in the container. Due to the containers' construction infants could feel only one object at the time but could pick out more objects than had been visibly added for the infant. Their search behavior revealed a correct understanding of the outcome of addition at 24-months of age but not at 18-months of age (see Starkey, 1992). This competence is much later than the age of five months as in Wynn's study. The age difference is difficult to explain in terms of rule-like computing processes. Perhaps, perception of numerical transformations might be better explained by processes that are dependent on the context in which addition takes place.

In the present study, we report an investigation of perception of the outcome of the addition (*1+1*) that resembles both the Wynn (1992a) and Simon et al. (1995) studies. Given the overall resemblance and the same design, our study is basically a replication of these two previous studies. It may establish the robustness and generality of the previous findings across investigations that are not exact replications. As in Wynn's and Simon et al.'s study, we tested infants' anticipation of the outcome of the addition (*1+1*) using the visual looking-time preference procedure. This procedure consists of a familiarization and a test phase. Initially, infants were familiarized to the addition (*1+1*). An addition was displayed by a manual pick-up event that is perceivable for infants of 7 months of age (Leslie, 1984), and consisted of two objects that were put one after the other into a kind of container and were never visible at the same time. So, we did not use a screen like Wynn (1992a) to hide objects, but used a container as Starkey (1992) had done. In the test phase, infants were presented alternately with the correct outcome (i.e., 2 objects) and the incorrect outcome (i.e., 1 or 3). If infants anticipate the outcome correctly, they should be surprised at the incorrect outcome, because their expectations are violated. This surprise may be revealed by longer looking times to the incorrect versus the correct outcome.

We did not include the deletion (*2-1*) into our study, but limited it to the addition (*1+1*). Both Simon et al. (1995) and Wynn (1992a) did not find a difference between perceiving the outcome of the addition and the deletion. Because we have found in our earlier study on perception of addition that perception of addition is not present at 8 months but may develop between 8 and 14 months, we again investigated these age groups, that is, 8- and 14-months-olds, respectively.

In addition to the replication of Wynn's study, which is the first experiment of our study, we also ran a second experiment. The second experiment tested whether any differences in looking times found for the incorrect (1, and 3) versus correct (2) outcome were indeed based on the surprise infants showed when their expectancy of the correct outcome of the addition (*1+1*) was violated. It could also be that infants always have longer looking times for 1 and 3 objects versus 2 objects out of some preference, and that this preference is unrelated to their perception of the addition (*1+1*) beforehand.

Experiment 1

An important difference between this experiment and Wynn's and Simon et al's is the way how the objects were consecutively concealed from view during the addition (*1+1*). For that purpose, we used a container that was put into view and over the object by the experimenter, whereas they used a screen that was mechanically raised in front of the object. All other procedural details in the present study were similar as in Wynn's. In the familiarization phase, infants looked at repeated presentations of the addition (*1+1*). The addition involved, first, the presentation of an object that was, then, concealed by view. Next, a second object, identical to the first, was brought into view by the experimenter and, following that, placed out of the infant's sight into the container. Thus, infants could repeatedly see the nature of the addition event (*1+1*) over time in the familiarization phase. In the test phase, infants were presented alternately with the correct outcome (i.e., 2 objects) and the incorrect outcome (i.e., 1 or 3). If infants perceived the outcome correctly, they should show surprise to the incorrect outcome, which may be revealed by longer looking times to the incorrect versus the correct outcome. We investigated two age groups, 8- and 14-months-olds, respectively.

Method

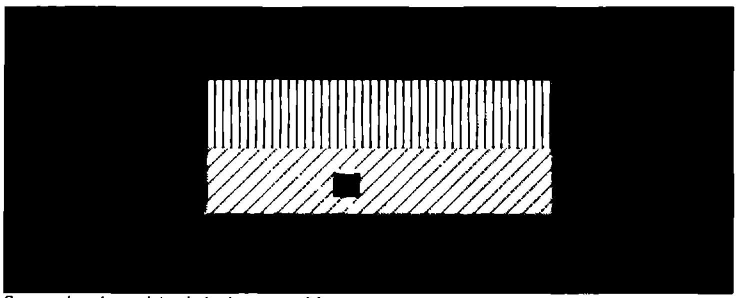
Subjects. Subjects were 14 infants of 8 months of age (mean age = 35 weeks; range: 30-37) and 20 infants of 13 months of age (mean age = 59 weeks; range: 52-64). There were no infants in either age group that were excluded due to fussiness or sleepiness during the sessions. In fact, no session at all was repeated because of problems due to infant's fussiness or sleepiness. Names and addresses of infants were obtained from the municipal government in Nijmegen. Parents were contacted by letter and after consent by telephone. No specific criteria for admission were used. Parents were financially compensated for their participation.

Materials. In an addition event, an experimenter visibly put an opaque container over one small, open tube that was already in sight. Then, he or she visibly put another tube into the container. Events were presented behind a window (70 x 35 cm) of a display cabin. In the display cabin, a occasionally in sight for the infants The window could be occluded by a screen that was operated by the experimenter Changes of displays between addition events took place behind the occluded screen The back side of the display cabin was patterned

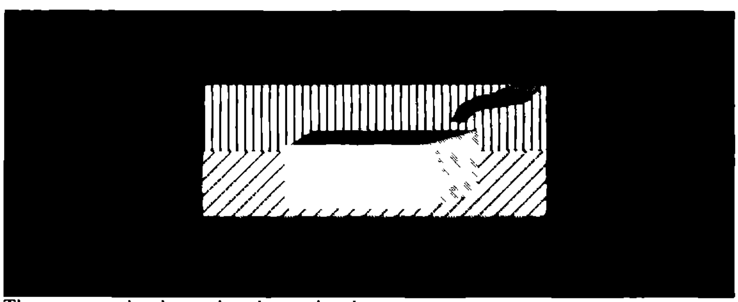
The tubes (4 cm in height and 4 cm diameter) were hollow, had neither a top nor a bottom and were made from red opaque plastic The container was 27 x 18 x 9 8 cm large, was made of the same red opaque plastic as the tubes and had neither a top nor a bottom, but only a small brim (3 8 cm wide) attached along the inner bottom backside on which a tube could be placed invisibly to the infant This was necessary for quick and surreptitious exhibition of all investigated outcomes of the addition (*1+1*) in the test phase (i e , 1 2, and 3 objects, respectively) The brim was covered with textile to prevent that any sound was produced, when a tube was put at or taken from this brim In order to ensure a constant duration of the addition event across habituation and test trials, the timing of the manipulation of tubes, container and screen was indicated by computer controlled graphics

Procedure. Infants were tested individually for the addition events in two separate, randomly ordered sessions The two sessions per infant were never on the same day, and generally had at least two days in between (mean intersession interval = 6 days) The procedure was equivalent for all sessions at both ages Infants were seated on the lap of their parents or caretakers in a dimly lit room at the university The room was only indirectly lit by a light bulb of 25 W in the display cabin Parents were blindfolded so that they could not look at the display Two parents objected to blindfolding and were allowed to participate in the experiment as long as they did not look at the display Because they did not, the data of their infants were included The infant's view of the environment other than the display was limited by surrounding screens By adjusting the height of the caretaker's seat, the eye level of the infant was set at the floor of the display cabin that supported the container In other words, infants looked at the frontal plane of the container but could never look into the container and see its content

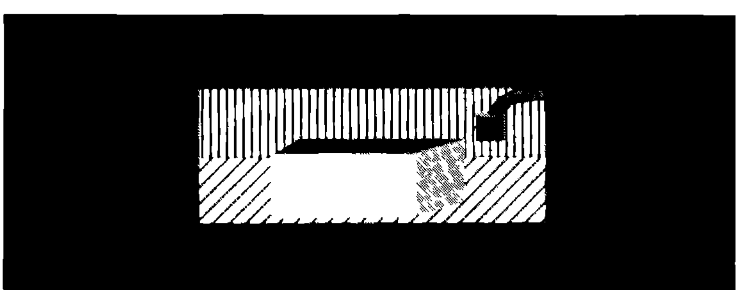
An infant-controlled habituation of visual looking time task was used Infants were habituated to the subsequent putting of two tubes in the container (i e , *1+1*). That is, the two tubes were never simultaneously in sight on habituation trials The beginning of each trial was signaled through a tone and the lifting of the screen of the display cabin A trial consisted of one or more complete presentations (i e , cycles) of addition events Addition events consisted of three phases after the lifting of the screen (see Figure 5a) First, one tube stood visibly for the infant on the floor of the display cabin Then the tube was concealed by the bottomless and topless container that was placed over the tube such that the infant no longer could see the tube. Following this, a second tube was added when the experimenter gradually brought a novel tube above the container while rotating it in the air to show it from all sides and to draw the infant's attention to this novel object. Then the experimenter put the second tube into the container, such that it was no longer visible to the infant. Finally, the container remained visibly in sight for the infant until the screen was lowered.



Screen has been lifted 1 object visible



The container has been placed over the object

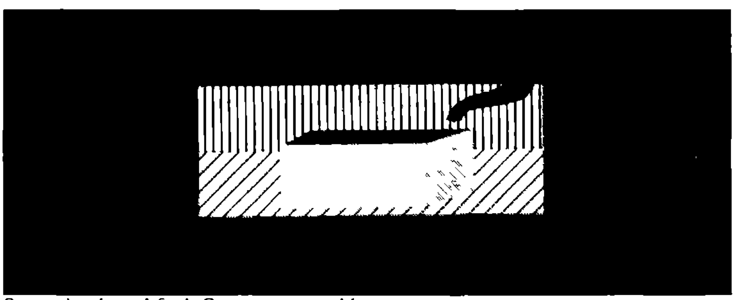


A new object is added into the container

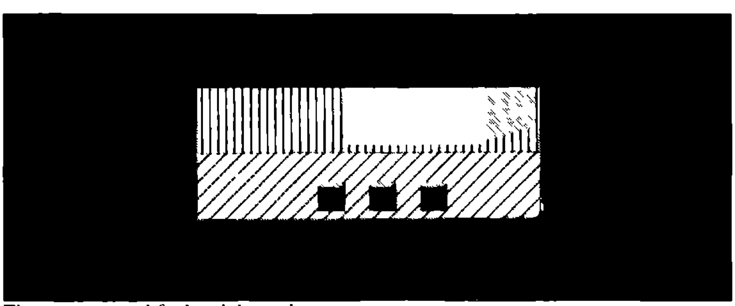
Figure 5a. The addition (1+1) on a habituation trial.

The three phases took 7.9, 7.5 and 2.3 s, respectively, and one complete cycle of an addition event took, thus, 17.7 s. Between cycles, the screen occluded the display for about 3.9 s. Between trials, the screen occluded the display for about 3 s. Note that during these trials the container was never lifted such that the infant could see the outcome during habituation.

A trial and the registration of visual looking time was stopped at the end of the first complete cycle in which either one of the two following conditions were met. The infant had looked away for 2 s continuously, provided that total looking time exceeded at least 1 s or the infants had a total of 10 fixations. Trials consisted always of one or more complete cycles of addition events. Habituation trials continued until the infant met the criterion of 50% or greater decrease in looking time on two consecutive trials relative to the total looking time on the first two trials of the habituation phase, or after a maximum of 13 trials. The computer calculated when the infant met the criterion.



Screen has been lifted Container is visible



The container is lifted and three objects appear

Figure 5b Presentation of 3 objects on a testtrial as the incorrect outcome of the addition (*1+1*).

After the habituation phase stopped, a test phase was started. On test trials, the addition event to which infants were familiarized was no longer presented. Instead on each trial a container was shown, that was subsequently lifted (see Figure 5b). When lifted it revealed 2 objects, i.e., the correct sum of the previously shown addition event, or 1 or 3 objects, i.e., the incorrect sum of the addition event. Presentation of both the correct outcome (i.e., 2) and the incorrect outcome took two trials each, and, thus, four trials totally. Presentation of the outcomes occurred in the following way. The beginning of each trial was signaled through a tone and the lifting of the screen in front of the window of the display cabin. The lifting of the screen revealed to the infant the container at the floor of the display cabin. Then the hand of the experimenter came into sight from the side of the window and moved towards the container. The hand of the experimenter lifted the container slowly and took it away to reveal the numerosity of the tubes. Each trial had the same total duration as the addition event in the habituation phase (i.e., 17.7 s).

The correct outcome of the addition (1+1) (i.e., 2 tubes) was presented on two so called C trials, and the incorrect outcome (i.e., 1 or 3 tubes) on two so called I trials. The C and I trials were presented in two different orders: C-I-C-I or I-C-I-C. These orders were randomized across two sessions. Sessions differed with respect to which incorrect outcome was shown on I trials, that is, 1 or 3 tubes. Order of sessions (i.e., I trial was 1 or 3) was varied across infants. The computer indicated to the experimenter which number of tubes should be revealed and how long the phases of this event took.

Looking times were recorded on-line by an observer through viewing holes in a curtain beneath the display cabin. An observer was thus unable to see the display. Fixations were scored with the aid of a button box connected to an Apple IIe computer. Observers were the same carefully trained persons as in our previous studies .

Results

Generally, infants were still attentive for the addition (1+1) at the last trial before the test phase. Eight-month-olds had a mean looking time of 15.5 s (SD = 9.8) and thirteen-month-olds had a mean looking time of 13.9 s (SD = 8.5), whereas the total length of an addition event took 17.7 s.

We reasoned that infants who are able to anticipate the outcome of the addition should be surprised and have longer looking times when they perceive a numerosity that was clearly not in accordance with the outcome of the addition (i.e., 1 or 3 tubes) instead of a numerosity that was in accordance with the outcome of addition (i.e., 2 tubes). This design allowed us to compare our study with Wynn's study (1992). We, therefore, analyzed preference for correct (i.e., 2 tubes) versus incorrect outcomes (i.e., 1 and 3 tubes, respectively) per age. In order to test this preference, we compared the looking times on trials showing correct outcomes (i.e., combined C trials) with looking times on trials showing incorrect outcomes (i.e., combined I trials). The looking times on C as well as I trials had a skewed distribution due to the fact that amount of looking time was to a large extent determined by the end of a cycle of an addition event. Following Winer (1971), we used a logarithmic transformation (log) to normalize the distribution. We tested the difference between C and I trials per age group (see Table 6 for the untransformed mean looking times for C and I trials per age group).

Table 6. *Combined Mean Looking Times for Age (8, 13 months), Outcomes (correct, incorrect) and Size (2 vs. 1 or 3)*

		Outcomes			
		2	1	2	3
Age		Correct	Incorrect	Correct	Incorrect
	8 months	30.0	33.7	30.4	37.3
		(16.0)	(20.3)	(11.9)	(19.4)
	13 months	44.3	48.9	36.1	50.4
		(31.6)	(28.2)	(17.9)	(33.8)

T-tests comparing mean transformed looking times on combined C and I trials revealed no significant difference at 8 months of age, t = -0.83, df = 13, p = .212, but a significant difference at 13 months of age, t = -1.96, df = 19, p = .033. To further explore the absence of significance at 8 months of age, we, first, conducted an ANOVA on transformed fixation times with the factors type of incorrect outcome (1 or 3), trial (correct and incorrect), and number of trial (first and second) which were all within-subjects factors. No significant effects nor interactions were found. In other words, also a more detailed analysis did not reveal any effect for 8-month-old infants.

In addition, we explored our findings that anticipation of outcome of the addition (*1+1*) developed between 8 and 13 months. Specifically, we analyzed whether our data show the developmental pattern found in some studies of the development of unity perception of objects (see Baillargeon, 1987; Spelke, 1994). That is, before development reaches a stable state, infants who habituate more rapidly also seem to have a greater preference for novel stimuli. Only in the transition stage, early compared to late developers showed a significant correlation between small total looking time across habituation trials and greater looking times on test trials. Before as well as after this transition stage, no such relationship was found. Therefore, we might expect a negative correlation between total looking time across habituation trials and higher looking times for incorrect versus correct outcomes at 8 months and no such correlation at 13 months. We correlated total looking time across habituation trials with the resulting proportion of visual looking time to the incorrect outcome (i.e., 1 and 3) divided by visual looking time to the correct outcome (i.e., 2). The results showed a significant, but instead of an expected negative, a positive correlation at 8 months (r = .39, p = .019, N = 28) and again a significant positive correlation at 13 months (r = .30, p = .032, N = 40). The results suggest, that those 8- as well as 13-month-old infants who explored longer across habituation trials, explored also longer the incorrect outcomes than the correct outcome on test trials. We, thus, did not find the relation of looking times that previous studies sometimes have found.

Next, we determined whether measurements of the habituation phase were different for the repeated presentation of the addition (1+1) in two sessions or for the two age groups (8 and 13 months, respectively). The habituation criterion, total looking time across habituation trials and the trial number in which the habituation criterion was met were entered separately in an Age (8 and 13 months) x Session (first and second) ANOVA of which the last factor was a repeated measurement. No significant main effects nor interactions were found, indicating that we found no support that the three measurements of the habituation phase differed for the two ages, or the two sessions.

Discussion

Our findings that infants of 13 months of age can perceive the outcome of the addition (1+1) replicate the findings of Wynn (1992) and Simon et al. (1995) that this perception is acquired in infancy. Our findings deviate from their findings with respect to the onset of the development. Their studies suggests perception of the outcome of addition at 5 months of age whereas our study suggests that it develops between 8 and 13 months of age. Although our study resembles Wynn's and Simon et al's, there are procedural differences. Wynn's study and, therefore, several procedural differences exist between her study and ours, it may be that any difference in procedure or design explains the differences in results. First, for example, we did not exclude infants from further analyses as Wynn did on the basis of greatly different pre-test looking times for either the numerosity 1 or 2 (in 16 out of 64 cases), or for 2 or 3 (a unknown number of cases). As a consequence, our study may have got a more conservative estimation of infants' understanding.

Second, both types of studies measured visual looking time of infants for the presented outcome of the addition, but the procedures differed considerably. Basically, we familiarized infants to the adding only and after a number of familiarization trials that was infant controlled, we presented them with test trials on which the correct or incorrect outcome was displayed. Simon et al. and Wynn used always a fixed amount of 6 trials totally on which a full addition was shown which had a correct outcome on three trials and an incorrect outcome on the other three.

However, we do not know of any systematic evidence that either one or a combination of these procedural differences could account substantially for the variation in age findings that seems to emerge across previous studies and our study. In our opinion, the most likely factor that may explain the different findings is the way how the two objects were subsequently concealed from view during the addition (1+1). For that purpose, we used a container, whereas Wynn and Simon et al. used a screen. As we will argue further in the *General Discussion* section, there are theoretical as well as empirical reasons to believe that the adding of objects into a container is more difficult to understand for infants than the adding behind a screen. Such an argument assumes, however, that 13-month-old infants showed longer looking times for incorrect outcomes versus a correct outcome because they related the number of objects that was shown on a test trial to the addition event across habituation trials and understood what the outcome of the addition (1+1) should be. In other words, infants would not have a preference for 3 and 1 objects over 2 objects on test trials that was unrelated to the addition manipulation event. We should therefore establish in a control experiment that the difference in looking times between correct and incorrect outcomes (2 versus 1 and 3, respectively) at 13 months was not the result of a sort of visual preference for 1 and 3 tubes over 2 that is unrelated to the addition (1+1) itself. In addition, the control experiment should establish that 13 month old infants can discriminate between the numerosities 1, 2, and 3 objects within the event of lifting up a container.

Experiment 2

The present experiment serves two purposes. First, it serves as a control experiment for experiment 1. We have argued there that the obtained results of the first experiment were based on anticipation of outcome of the addition (1+1). However, infants' longer looking times for incorrect outcomes (i.e., 1 and 3) versus correct outcome (i.e., 2) might be based on a yet unknown preference pattern. We investigated the presence of preference patterns by assessing looking time patterns for events that consisted of revealing 1, 2 or 3 objects by lifting a container as on test trials in the previous experiment. If there would be no difference in preference for uncovering of 1, 2 and 3 tubes, initial looking times to this event should not differ. Because we had no significant findings at 8 months of age, we ran the control experiment only for 13 month-old infants.

The control experiment served the additional purpose of replicating previous findings of numerosity studies for 13-month-olds (e.g., Strauss & Curtis, 1979; van Loosbroek & Smitsman, 1990). A replication of this finding would show that infants can discriminate small numerosities. That is, in three sessions infants were habituated to the numerosities 1, 2 and 3, respectively, and were presented with a novel numerosity on test trials that was always one greater than on habituation trials (i.e., 2, 3, and 4, respectively). To measure infants' preference for either 1, 2, or 3 objects, the looking times for the first two habituation trials were used.

Method

Subjects. Twelve infants of 13 months of age (mean age = 60 weeks; range: 56 - 63 weeks) participated in this control experiment. One infant was excluded from the final analyses because the parents refused to participate anymore after two sessions. Two experimental sessions were interrupted because of technical problems with the time registration equipment, and were repeated later.

Materials. We used the same display cabin, container, and tubes as in experiment 1.

Procedure. Infants were tested individually for the three numerosities (1, 2, and 3) in three separate, randomly ordered sessions that were never on the same day but generally had at least two days in between. As on test trials in the previous experiment, presentations on habituation and test trials always involved the showing of the container, and the subsequent lifting of the container to reveal a certain number of tubes. The experimental procedure had the same characteristics as in experiment 1 concerning blindfolding of the parents, time schedule of manipulations, as well as criteria for stopping trials and stopping the habituation phase. After habituation to the numerosity 1, 2, or 3, the test phase started. The test phase consisted of four trials in which the old numerosity was again shown on two O trials and a new numerosity on two N trials. Novel numerosities were always one greater than the old numerosity (i.e., 2, 3, and 4, respectively). There were two orders of presenting O and N trials: O-O-N-N and N-N-O-O. Session order (i.e., numerosity 1, 2, or 3) and test trial order (i.e., O-O-N-N or N-N-O-O) were randomized.

Results and Discussion

First, we examined whether the longer looking times to the numerosities 1 and 3 than to the numerosity 2 obtained in experiment 1 were not based on some kind of natural looking preference but were indeed based on anticipation of the correct outcome of the addition (*1+1*). In that experiment, the critical comparison was based on the combined looking times within subjects for a so called 'incorrect' (I) outcome (i.e., the numerosities 1 and 3) versus 'correct' (C) outcome (i.e., the numerosity 2). These combined looking times were then normalized through a logarithmic transformation. In a similar way as in that experiment, we compared in the present experiment the combined transformed looking times on the first two trials of the habituation phase for the numerosities 1, 2 and 3, respectively, in a MANOVA with numerosity as a within subject-factor. No effect was found, $F\ (2,10) = .42$, $p = .67$, indicating that for the group of 13-month-olds visual attention to these three numerosities did not differ, and more specifically, that visual attention to the numerosity 2 was not significantly less than to the numerosities 1, and 3.

In our second analysis, we attempted to replicate whether 13-month-olds can discriminate between small numerosities. For that purpose we always compared combined N trials showing a new numerosity with the previous two trials showing the old numerosity. That is, when N trials were in the order of O-O-N-N their looking times were compared with the looking times on the O trials, whereas in the order of N-N-O-O, looking times on N trials were compared with looking times on the two last habituation trials. In the latter case, our analysis followed the design of previous studies (see chapters 2, 3 and 4). Combined looking times were logarithmically transformed. A 3 x 2 MANOVA with numerosity (1, 2, and 3) and trial (O and N) as within-subjects factors yielded only an expected significant main effect for trial ($F\ (1,11) = 4.52$, $p = .029$), indicating that infants discriminated between the numerosities 1, 2 and 3 and numerosities that were one greater (i.e., 2, 3, and 4).

In sum, the present control experiment allows us to conclude that the difference in preferences found in experiment 1 can be ascribed to anticipation of the outcome of the addition (*1+1*) at 13 months of age.

General Discussion

In our study, 13-month-old infants understood that the outcome of the addition (*1+1*) should be 2 and not 1 or 3 objects, whereas such an understanding was not found in infants of 8 month old. In a control experiment, we showed that the results at 13 months could not be explained on the basis of a visual preference for the particular numerosities of 1 and 3 over 2 objects, although infants were able to discriminate these numerosities. Moreover, we demonstrated that these infants could discriminate between these numerosities.

Clearly, we did not replicate the results obtained by Simon et al. (1995) and Wynn (1990). These studies found anticipation of outcome of the addition ($1+1$) already at 5 months of age. On the other hand, the present findings are in line with a number of other studies on perception of addition (e.g., Arterberry, 1995; see also Chapter 4). For example, Arterberry found that perception of a small numerosity of elements (i.e., 2) that one after another appears through an aperture develops between 10 and 12 months of age. Overall, these discrepant findings suggest that infant's understanding of addition is strongly affected by how addition events are displayed. In the following, we will present an argument why these task variations may explain the different age findings and to what extent.

In the present study, addition was displayed by the subsequent concealment of two objects. First, an object was covered by a container, then a second object was put into the container. Anticipation of the outcome of this transformation is possible, if information is available about the persistence of the objects involved in the addition transformation and if infants are able to pick up this information. Infants perceive the unity and boundedness of objects in sight already by 3 months of age (see Spelke, 1990). It is less clear whether infants generally perceive the persistent unity and boundedness of objects that go out of sight irrespective of the way it happens. Going out of sight involves a rearrangement of an object with respect to its surrounding environment. Infants of 5 months old perceive the persistence of an object when the rearrangement involves concealment of an object by a screen (Baillargeon, Spelke, & Wasserman, 1985). In this case, the screen occupies a different space than the object. However, concealing an object by a container may be problematic, because the space occupied by the container includes the space occupied by the objects that are concealed. The container and the contained objects no longer involve separate spaces, whereas exactly occupation of separate spaces appears to be a precondition for perceiving the unity and persistence of objects at an early age (see Spelke, 1990). With respect to containers, Bower (1979) specifically hypothesized that infants believe that '...only one object can be in one space...' (p. 154). If infants are unable to obtain information about unity and persistence under conditions of containment, infants might belief that objects go out of existence when they go out of sight once they are concealed by an opaque container. Consequently, it would be hard for them to perceive the numerosity of objects that resulted from such transformations.

Quite a few studies investigated perception of containment (e g , Caron, Caron, & Antell, 1988, Pieraut-Le Bonniec, 1985, Sitskoorn & Smitsman, 1995) At least, their results are consistent with the conclusion that relations of containment are problematic for infants as young as 5 months of age More specifically, the study by Pieraut-Le Bonniec (1985) seems to indicate that infants have problems picking up information about the inner properties of hollow objects Perhaps, initially infants do not explore the inner properties of objects, because this exploration is dependent on the same initial constraints on unity and boundedness that led them to believe that objects cannot occupy the same space, and, thus, cannot be hollow

Our analysis of containment and its empirical evidence suggest that it is more problematic for infants to be aware of the persistence of objects when they are concealed by a container, as in the present experiment, than by a screen, as in Simon et al 's and Wynn's study If such would be the case, the different age findings that were obtained across these two types of addition studies can then be explained as a task effect The task for infants was to anticipate the correct outcome of addition based on transformation that was used to display addition of objects during habituation In our view, this task factor can substantially account for the relatively great age difference between the present study and those of Simon et al and Wynn Specifically, the contrasting findings of the age of 5 months, on the one hand (Simon et al , Wynn), and between 8 and 13 months, on the other hand (the present study), suggest that the difference is profound and may have implications about how development is conceived

If one has a cognitive view on the development of addition and conceives the anticipation of outcome as the result of computing processes (see Wynn, 1992), effects due to task factors may seem trivial because they simply show whether the proper assessment procedure was used to optimally measure the infant's capacity, or not However, if one conceives the understanding of addition as intrinsically related to the development of perceptual processes that sample information about the unity and persistence of objects parallel to the unfolding of addition events, task factors are important Task factors involve constraints for sampling processes The dynamical approach (e g , Thelen & Smith, 1994) provides theoretical arguments for why effects of these constraints are of relevance to hypotheses about the development of numerical skills For example, it may be hypothesized that perception of addition evolves along different paths for addition transformations that constrain sampling of information about unity and persistence in qualitatively different ways (e g , concealment by a rotating screen or concealment by a container) Only subsequently, and due to repeated experience with other addition events, distinct perceptual processes for addition transformations become more entrenched, automatic, and more general by their coupling to other processes.

Task variation may continue to have an effect on infants' anticipation of the outcome of addition after 13 months. Starkey (1992) used a manual search task to investigate infants' anticipation of the outcome of the addition (1+1) in terms of correct (2) or incorrect (1, 3) outcomes. Also in this study, objects were put into a container. His results revealed a search for the number of objects that generally matched the correct outcome of addition at 24-months of age, but not at 18-months of age. This understanding is, thus, acquired much later than either the age of five months as in Wynn's study, or the age of 13 months as in our study.

So far, we have argued that task factors, such as type of transformation, that affect perception of an object as a persistent unity also affect perception of the numerosity of objects that result from addition. There are points to be noted with respect to this conclusion. It seems quite evident that not every difference in findings can be accounted for by the same task factor, or even by one task factor alone. For example, it is not completely clear what task factor(s) exactly may account for the difference in age findings of Arterberry (1995), on the one hand, and the findings of Simon et al. (1995) and Wynn (1992), on the other hand. Arterberry (1995) found evidence for perception of addition at the age of about 10 to 12 months, which is much later than the age findings of. for example, Wynn. Both Arterberry's and Wynn's studies investigated addition of two objects that either one after another appeared through an aperture, or were one after another concealed by a screen, respectively. Apparently, more research is needed to provide a complete account of different findings.

Furthermore, task factors cannot account on their own for age differences. It is very likely that task factors affect perception in interaction with a general maturation of the perceptual system. Perhaps, this explains why, for example, our previous study on addition (Chapter 4), and Arterberry's study (1995) both have age effects later than Wynn's and Simon et al.'s studies, but somewhat comparable to the present study (i.e.., between 10 and 12 months of age).

Perception of addition is not always affected by factors that are known to affect object perception. Infants perceive a disappearing object as persistent, and, moreover, they perceive which object disappears. However, a recent study (Simon et al., 1995) suggests that when two objects one after another disappear, infants perceive their numerosity but no longer which objects exactly disappear. Apart from replicating the study by Wynn, Simon et al. introduced as a variation in the design the occurrence of novel objects. In some conditions, the outcome in terms of number of units (either correct, 2, or incorrect, 1 or 3) involved units that had not been used before in the addition. For example, when Sesame Street puppets were used and two Ernies were one after another added behind a screen, the outcome involved one Ernie and one Cookie monster instead of the expected two Ernies. Infants of 5 months of age were, however, only surprised when the numerosity outcome was incorrect. They were not surprised when the correct or incorrect outcome involved puppets they had not seen before, although a control study clearly showed that infants could discriminate between the two types of puppets.

Perception of the numerical outcome of addition extends object perception in the sense that more than one object is involved. No investigation has yet been reported that assessed whether infants can anticipate the outcome of greater additions than (*1+1*), such as (*2+1*) or (*1+1+1*) or (*1+2*), or greater deletions than (*2-1*), such as (*3-1*) or (*3-2*). Judging from the development we have found so far, we may hypothesize that infants gradually acquire the outcome of greater additions than (*1+1*) after they have acquired the addition (*1+1*). In other words, we predict that increasing the number of units in the addition poses problems for the infants' monitoring of how many elements result from the addition event. To differentiate units within the structure of an addition event and to keep track of their persistence may be more difficult for more units. Evidence from a search task (Starkey, 1992) supports our hypothesis that generalization of understanding the outcome of the addition (*1+1*) to the addition (*2+1*) may be not automatic for perceptual development and may take some time if it indeed reflects a clear developmental step.

6 General Discussion and Conclusions

We discuss the findings from our studies and evaluate the evidence in terms of the underlying processes and the developmental mechanisms We also relate our findings to other findings in the area of numerosity understanding in infancy. We argue that the findings can be explained by a perceptual model of numerosity understanding and not a cognitive one

Basic findings

In a series of studies, we addressed the basic question of whether and how infants visually perceive numerosity of a collection of objects. In particular, what are the processes that enable infants to perceive numerosity? We assumed that the processes in numerosity perception develop from unity information that infants obtain through exploration of objects over time. We, furthermore, assumed that infants detect numerosity by the organization of their perceptual activities with respect to units. If infants pickup unity information, the perceptual activities involve keeping track of the units that are available over time and space. We supposed that these activities are affected by the number of elements and, thus, become differently organized when different numerosities are explored. In general, the organization of these activities is dependent on spatial and temporal properties of objects and affects how well infants can detect and stay attuned to unity information. One such property is numerosity. Other possible properties are type of object motion (e.g., rotary, pendular, or elastic motion), relative positions of objects, and shape of objects.

In our first study (Chapter 2), we tested whether discrimination of unity and boundedness of elements underlies numerosity perception. Under unimpeded motion, objects specify their unity and boundedness even when they occlude. By moving objects and shifting their positions relative to one another, we were able to show that discrimination of units underlies numerosity perception in infancy and that discrimination of characteristic static patterns that are confounded with numerosity, such as a triangular configuration for three elements does not underlie numerosity. Numerosity perception was demonstrated for infants from the age of at least 5 months. The numerosities we investigated were small and ranged from 1 to 4 objects. Clearly, infants can perceive numerosity as an invariant property of collections composed of objects that change position continuously and may occlude one another.

The second study (Chapter 3) investigated in more detail the information that enables infants to perceive numerosity for a collection of distinct elements. Similarity of shape has been proposed as a source of information. Numerosity perception would operate as a categorization process that initially required homogeneous objects or, at least, objects with great similarity of shape. In contrast, our hypothesis further elaborated on our view of numerosity perception as involving search processes that accumulate distinct elements on the basis of their unity information. Our hypothesis, thus, predicted that similarity of shape would not provide a basis for numerosity perception in infancy. The results supported our hypothesis and demonstrated that infants from 5 months old are able to perceive numerosity of a collection of heterogeneously shaped objects. Interestingly, 5-month-old infants perceived the numerosity of collections of three but not of two objects. Perhaps, exploration of the shapes of elements interferes with the search for unity information. Thus, shape discrimination would be easier for two objects than for three, especially when their trajectories change and occlusions occur. In contrast to younger children, 13-month-old infants discriminated all numerosities that were presented. This suggests that numerosity perception becomes more task oriented with increasing age and less easily side-tracked by exploration of individual elements.

These two studies are the first in the area of numerosity perception to use elements in motion. Previous studies always used displays always consisting of stationary elements. Our studies replicated previous findings (e.g., Starkey & Cooper, 1980; Strauss & Curtis, 1981) that infants can perceive small numerosities (1-4) and extended our knowledge of what numerosity perception in infancy may involve to include the property of motion. We will argue in the next section that these results provide evidence that numerosity is perceived through explorative activities on bounded and unified elements. Finally we believe our findings also extend the insights on how numerosity perception in infancy may develop.

Numerosity does not always remain constant, but may change through transformations such as addition of an element to another element (i.e., *1+1*). With perceiving addition, infants also keep track of numerosity over time. We investigated perception of addition in the next two studies of the present thesis (Chapter 4 and 5).

In the third study (Chapter 4), we investigated infants' perception of one added element. Did infants keep also track of the numerosity of a collection of elements that increased through addition of another element? One element came into view from the edge of a TV monitor and was added to element(s) already present on the screen. For an addition event (e.g., *1+1*), the numerosities involved over time are the initial or augend collection (i.e., *1*), the addend or the numerosity of objects that are added (i.e., *1*), and, finally, the numerosity of the sum collection of objects that result after the addition (*2*). The results of this study showed, however, that infants did not start discriminating numerosities of an addition until 8 to 14 months of age, and even the 14-month-olds could not discriminate all changes in numerosities over time. At this age, infants perceived that no addition occurred as well as a larger addition. Infants did not perceive that an addition occurred with a smaller augend collection. In other words, infants did not perceive the numerosity of the initial collection of elements when, soon after presentation, it is changed through addition. But our previous studies have shown that infants can perceive the numerosity of a collection of elements that remains constant.

These findings were inconsistent with the view that infants anticipate the outcome of an addition by computing this outcome from the numerosities of the initial augend and the addend. At 5 months of age, infants did not discriminate any component of an addition event although anticipation of the outcome of addition has been demonstrated at this age (see Wynn, 1992). We explained our results in terms of infants' perceptual activities and, specifically, in terms of the problems infants might have with keeping track of the elements in the addition event.

Since the results on perception of components of addition were not in accordance with the hypothesis that the outcome of addition is computed from augend and addend, we conducted a new study on the perception of the outcome of addition. This study was comparable to previous studies on the outcome of addition. In our fourth study, we investigated whether 8- and 14 month-old infants anticipated the outcome of an addition. The addition that was shown involved one object that was placed into sight and then concealed by a container. A second object was shown and put into the container (i.e., *1+1*). Fourteen-month-olds anticipated that the outcome of this addition would be two, and not one or three objects, whereas 8-month-old infants did not. These results deviated from previous studies of addition ($1+1$) (for example, Simon et al., 1995; Wynn, 1992a), suggesting that perception of the unity and persistence of objects within a container might be problematic for younger infants, because the space occupied by the container includes the space occupied by the objects in the container. This view is in accordance with the argument that occupation of separate spaces is necessary for infants' perception of the unity and persistence of objects at an early age (Spelke, 1990).

To explain the findings, we discussed the significance of exploratory activities over time that sample unity and persistency information. We further proposed that spatiotemporal properties of displays containing figures constrain these activities and affect the outcome of these activities. In this respect, numerosity perception of elements presented simultaneously or sequentially does not involve fundamentally different processes (but see Cooper, 1984; and Harris, 1985 for a different view). Both involve search activities over time. Both involve sampling of unity information. They may, however, differ in the extent to which their displays allow adequate sampling and monitoring of the number of elements for which unity information is obtained.

These studies provide insight into important mechanisms for the perception of and development of numerosity. Our results converge with previous findings that suggest numerosity is still developing from the age of 5 months on and proceeds in close relation or parallel with the development of object and event perception.

Processes

Numerosity may be considered as an abstract property of a collection of elements. To be combined to numerosity, these elements require No other property than the element's unity and boundedness makes elements in a collection perceivable in terms of numerosity. It does not matter whether these elements have similar shapes or very different ones, or whether these elements are displayed in one configuration or another. Under all circumstances, numerosity exists as long as elements exist. Whether they are visual or auditory elements does not matter.

There are two models of numerosity, the counting model (e.g., Gelman, 1990; Gelman & Greeno, 1989), or its recent formulation the accumulator model (Gallistel & Gelman, 1992) and the one that we propose: that numerosity is perceived through activities searching for unity information about elements. According to the counting model, numerosity is computed by incremental, counting processes that operate on representations of elements. These representations are structured according to implicit counting principles such as the one-to-one principle which allows representations that preserve the discreteness of elements and yet unites the elements comprising a collection. The one-to-one principle is theorized to be visible in the way the internal mechanism maps the numerosity to the mental magnitude that represents it. This mental magnitude changes when states of the accumulator change parallel to the number of elements in the collection. However, states of the accumulator are not affected by the spatiotemporal properties that constitute the displayed context for elements. In our studies, we found that numerosity perception is dependent on context; thus, the variability of the outcome of infants' search processes cannot easily be reconciled with the general tenets of the present counting models.

The counting model assumes that non-verbal representations are ordered, presumably parallel with increasing numerosities. According to Gallistel and Gelman (1992), representations are generated when an element is encountered, because a neural pulse is triggered that passes through a gate into an accumulator. Something like the gradations on the accumulator would indicate the number of elements in the collections. If such an incremental counting process would exist, it is not clear why numerosity perception of 5-month-old infants failed for a collection of two heterogeneously shaped elements, but was successful for a greater collection that consisted of three heterogeneously shaped elements (Chapter 3).

Our findings about perception of the addition event (*2+1*) (Chapter 4) suggest a re-evaluation of the proposed mechanisms in preverbal counting. An incremental process suggests that children keep track of numerosities presented as a collection of elements that grows incrementally by the appearance of a new object. However, infants of 14 months of age did not discriminate between the addition events (*2+1*) and (*1+1*). These addition events differed if either initial numerosities (*2* vs. *1*, respectively) or sum numerosities (*3* vs. *2*, respectively) were counted. Additionally, although infants could not count in the previous condition, they could in the two conditions that, one, involved a larger addend (i.e., +*2*), or, second, no addition at all (i.e., *3*) but that remained the same in terms of the sum of elements . Furthermore, the counting model does not account for why perception of numerosities within the addition event (*2+1*) is present no sooner than 14 months of age (chapter 4), whereas 8-month-olds perceive numerosities such as 2 and 3.

Verbal counting has been shown (Fuson, 1988) to be much more variable than was expected on the basis of the counting model of Gelman and her associates (Gelman & Gallistel, 1978). Verbal counting does not rely on a uniform counting activity. Similarly, our findings show that infants' knowledge of numerosity is much more variable and differentiated than might be expected from the counting model for numerosity perception. Our findings may be explained by the development of coordinated activities in numerosity perception.

We argue that, in our view, visual perception of numerosity is the result of a system that over time coordinates its activities on the basis of information that exists in the relation between environment and perceiver (Gibson, 1979). Information about perceivable units that can be enumerated may be picked up by a perceiver. Units in the environment are structured at various levels of size (for example, people, their hands fingers and so on). Unity information is also available no matter whether the elements are places, events or objects. In addition, unity information is available for different modalities of perception, such as the visual, auditory, and haptic system. We have restricted our studies to visual perception of objects, and, especially, to detached objects such as persons as opposed to attached objects such as hands. A detached object refers to a layout of surfaces completely surrounded by the medium (see Gibson, 1979). Such an object especially specifies its unity and boundedness when it has common motion of its surfaces with respect to surrounding surfaces that entail other objects. In addition to motion, other sources of information that specify object unity are alignment and relatability of edges and three-dimensional depth cues such as binocular disparity (see Johnson & Aslin, 1996).

Numerosity perception involves the pickup of unity information but this does not occur without effort. The effort is revealed by long looking times across many trials in some of our habituation experiments (e.g., see Chapters 4 and 5) when infants sample unity information across distinct and segregated elements in an array and over time. The effort may also be involved if we hypothesize correctly that it takes time for young infants to get their perceptual activities organized and to attune sampling to properties of a particular displayed collection of moving element. The specifics of how these activities are organized and how this organization varies for different numerosities is not clear from the present findings. To further clarify these activities, experiments may be designed that register on-line processing and its organization.

We also need more direct evidence on how unity information is obtained across distinct elements. At least, unity information may be obtained sequentially with one unit at a time. The ability of infants to visually perceive numerosity and anticipate the number of an element on the basis of presentations of elements one at a time provides evidence for sequential sampling (Canfield & Smith, 1996). In addition, the process of sequential sampling of one element at a time is consistent with infants' ability to perceive numerosity amodally for stationary elements presented visually on pictures and distinct sounds such as drumbeats that accompanied the visual displays (see Starkey et al., 1983, 1990; Moore et al., 1987). Other possibilities, such as sampling of unity information for two objects at once that are closely together in space, have not yet been systematically investigated.

If infants perceive numerosity, they exhibit ongoing coordination of processes that keep track of objects over time and space. Thus, infants' perception is selective and well organized in sampling unity information. At the same time, infants ignore properties of the display that are irrelevant to numerosity perception, such as patterns that arise across motions (e.g., see van Loosbroek & Smitsman, 1989). In contrast, Gelman (1990) has maintained that numerosity perception is selective because it is guided by cognitive principles. Thus, numerosity perception is supposedly based on inferential processes and guided by counting principles which may be present from birth.

In our view, however, numerosity does not exist outside nor beyond the context in which the perceptual processes are invoked in the search for unitary elements. Following the dynamic systems approach (Thelen & Smith, 1994), we assume that numerosity perception in infancy may be selective by itself if it consists of self-organizing activities that are attuned to unity information across elements. Further, we suggest the preferred organization by the visual system varies for different numerosities. This preferred organization is a function of the interactions of visual subsystems and their sensitivity to external conditions such as the displayed elements. Thus, numerosity emerges over the course of visual perceptual activities and is based on processes constrained by the elements and their number when they are searched for unity information.

Many researchers assume that numerosity perception in infancy is limited to small collections of elements with an upper limit somewhere around 4 elements (e.g., Starkey & Cooper, 1980; Strauss & Curtis, 1983). In our model, we also assume that the possibility to keep track of elements is constrained by their number. When too many elements are present, there may be too few constraints for the infant's perceptual system to keep track of objects over time and space and discrimination of numerosity may not occur (Smitsman, 1996). The limit beyond which discrimination does not occur is probably not fixed to a particular numerosity but depends also on how collections of elements are displayed.

Our two studies on perception of numerosity as an invariant property (Chapter 2 and 3) did not reveal a clear cutting-off point specifying when infants can perceive numerosity. One explanation for not finding a clear upper limit was the great variability in looking behavior within infants across different presentations of the numerosities presented (see e.g., Chapter 2). Our displays included many properties to attend to in addition to numerosity (such as figures moving along irregular trajectories). These other foci of attention may distract infants from activities necessary for numerosity perception leading to great variability of looking behavior within and between individuals.

As with earlier studies on this topic (Canfield & Smith, 1996; Simon et al., 1995; Wynn, 1992a), we did not systematically investigate the upper limit for the number of elements for perception of addition (see Chapter 4 and 5). Future studies should address this topic. These studies may allow a comparison of upper limits for displays of simultaneously presented elements and elements that are presented one after another, and may imply conclusions about the mechanisms of numerosity perception. They may imply that simultaneously presented elements allow for more exploration than elements presented one after another. For example, elements that are simultaneously presented differ from elements that are represented one after another in that they may be extensively explored for numerosity. If exploration of unitary objects is somehow disturbed, only simultaneously presented objects may be again explored. Do infants use this possibility and is this reflected in the maximum size of collections for which they can perceive numerosity? On the other hand, more exploration may involve elements but may also involve properties of the display that do not underlie numerosity, and, thus, divert attention away from numerosity.

Our study on numerosity perception for heterogeneous shapes (Chapter 3) suggests that 5-month-old infants' attention is easily diverted to properties such as contour when the displayed numerosity consists of two simultaneously presented elements. By contrast, Simon et al. (1995) suggested that 5-month-old infants did not perceive the shape of two elements presented successively but only their numerosity. Although there were many differences between the two studies, looking at the context of elements in more detail may eventually allow for more definite generalizations about numerosity perception and its constituent processes such as object and event perception.

In addition, the upper limit may not only be dependent on how a collection is displayed but on how the infant's task is designed. The upper limit of numerosity perception may only be apparent if infants have to compare two collections that differ by just one element and may shift upwards if numerosity differences between collections are larger than one element (see van Oeffelen & Vos, 1982). Although many developmentalists assume that comparisons of collections of elements that differ in size by just one element is numerosity perception, and comparisons of collections that differ in the size by more elements than one is numerosity estimation (e.g., Davis & Pérusse, 1988; Strauss & Curtis, 1984), it is unclear yet to which extent the organization of perceptual activities is different and involves different subsystems for both skills.

In sum, to further address how processes evolve during numerosity perception, we need to investigate more directly these processes in real time. So far, perceptual activities such as scanning that go beyond exploration of one stationary object and concern collections of objects have been scarcely investigated in infancy despite their ubiquitous importance in perception and its development (e.g., see Aslin, 1985). In numerosity perception, for example, when a collection consists of elements that are all simultaneously shown on a small TV screen, we may investigate how infants' iterative scanning of elements occurs and how this scanning is affected by the displayed collection. Similar perceptual activities may be followed, when distinct elements are in sight one after another. Investigation of numerosity perception in real time may also provide evidence whether they can be described within a dynamical systems model (see Thelen & Smith, 1994). So far we have interpreted numerosity perception in terms that are consistent with this model because we have described numerosity perception in terms of self-generated perceptual activities, that evolve over real time and that are context dependent. Additional investigations should provide a clear test of hypotheses that are implied by this model.

Development

In our view, numerosity perception consists of perceptual activities that evolve over time when an infant's visual system is attuned to unity information. This may involve a series of trials across which infants form expectations of the size of a collection of elements, and are surprised and explore the collection more extensively if they suddenly perceive a collection of a different size. A dynamic systems approach to development (Thelen & Smith, 1994) assumes that the processes of an infant's visual system when focused on a particular display, also happen over longer time periods (i.e., across weeks and months). Due to increased experience with collections of elements of different sizes, expectations become stabile and easier to generate. By then, the visual system has developed a stable organization of perceptual activities that is realized for many similar events.

As long as this development is not complete, and a stable organization has not been reached, perception of numerosity is easily disrupted by specific properties of the display. Our studies show, in general, that the development of numerosity perception is not complete at 5 months of age. When elements are simultaneously presented, numerosity perception is easily disrupted by properties such as parallel movement patterns across elements (van Loosbroek & Smitsman, 1989), and heterogeneity in the shape of the elements in the display (Chapter 3). the results of these two studies demonstrate that discrimination of small numerosities appears easily disrupted (2-1, 2-3, and 3-2 in van Loosbroek & Smitsman, 1989; and 2-1 and 2-3 in Chapter 3). We attribute these results at 5 months of age to young infants' tendency to explore the pattern of movement or the shapes of elements while losing track of unity information across elements. With greater numerosity, the display of moving and occluding elements afforded infants' exploration of numerosity more easily.

These studies demonstrate another interesting pattern. At the age of 5 months, infants do not always seem to discriminate between greater numerosities when elements are displayed simultaneously (4-3 and 4-5 in the longitudinal group in Chapter 2; 4-5 in the complete group in Chapter 2; 4-3 and 4-5 in Chapter 3; 4-5 in van Loosbroek & Smitsman, 1989), but at later ages they consistently discriminate between greater numerosities. These findings demonstrate that the ability to keep track of the number of elements improves over time.

In addition, the result of our study on the perception of the components in addition (Chapter 4) demonstrated that the perception of numerosity can be disturbed. Keeping track of numerosity may be disturbed when an element is added to a collection of elements. Increasing economy and specificity of numerosity perception develops for 5 to 13 month old infants. Keeping track of components within an addition event (*2+1*) such as its augend collection (i.e., 2 elements), or its addend (i.e., 1 element) appears to develop between 9 and 14 months of age (see chapter 4). Disturbance of numerosity perception may have occurred because the presentation of the augend collection occurred when exploration activities were starting to become attuned to the two moving elements already present. Before activities were fully attuned to the available sources of unity information, another element came into view and this may have disrupted further attunement in 8 month-old infants. Thirteen-month-old infants also lost track of the numerosity of the augend collection after the addition of another element, but at least they attended to the numerosity of the elements added.

The development of increasing economy in information pickup has been described as typical for the development of object exploration at 5 months of age, and is attributed to several factors: increased visual acuity, maturation of visuo-motor components of tracking, and increased skill of reaching (E.J. Gibson, 1988; pp. 19-20). These components must develop before they can get coordinated and organized. Around this age, however, not only do general exploration activities need more development, but the pickup of unity and persistency information is not fully differentiated yet (see Johnson & Aslin, 1996). Our study on the anticipation of the outcome of addition also supports this idea.

In our study on the addition of two elements into a container (see Chapter 5), we found the development of numerosity perception between 8 and 14 months of age, that we explained as being the result of an increasing differentiation of persistent and unitary objects. Initially, infants may not perceive contained objects as distinct and separate from the container. When infants grow older, they learn to understand that a bounded, unitary but hollow object without a top can contain other bounded, unitary objects.

Such findings suggest that the perception of numerosity is related to the perception of unity and the persistence of elements. Numerosity perception reveals the upper limit of the number of elements that infants can keep track of in their search for unity information. Gradually, infants seem to pick up unity information for objects under more and more circumstances. For example, they perceive it not only on the basis of a common, translatory motion (either laterally, or in depth) but they also perceive it for stationary objects and objects that are perceived when the perceiver is moving (e.g., see Kellman, 1993).

The developmental changes thus far are not unique for numerosity perception because they also affect the basic processes that comprise numerosity perception (e.g., the pickup of unity information). At some point in development, we may, however, see changes that are tied to the development of number such as the understanding of change in numerosities. For example, exploration of unity information does not suffice to understand that addition of one element to one element (i.e., *1+1*) or one to two elements (*2+1*) is the same type of change (an increase of one element) in contrast to the deletion of one element from two elements (i.e., *2-1*), which involves a decrease with one element. Preliminary findings (van Loosbroek & Smitsman, 1987) suggest that infants start understanding these relations of change rather late in development (after 13 months of age). Processes that involve abstraction and generalization across numerical transformations seem necessary to understand the similarity and differences of all additions of one element, and, for example, deletions of one element. Developmentally, it may take a distinct, developmental step to perceive similar relations of change across numerosities, including the type of change (i.e., addition as opposed to deletion), or the size of change (additions of one as opposed to two elements). This developmental step may be grounded in previous developments of numerosity perception and forms an extension of it.

Understanding of ordinality across numerosities may reflect a similar developmental step. Understanding of ordinality involves understanding relations of "more than" or "less than" across numerosities. For example, the numerosity orders 1-2 and 2-3 are relations involving more and a relation such as 3-2 involves a relation of less. The understanding of order relations across numerosities gradually develops after 13 months of age (e.g., see Cooper, 1984, 1985).

Numerosity perception in infants is an adaptation to the environment that allows for the comparison of collections in terms of their size. This adaptation to explore collections of elements is characteristic of many biological systems, including humans, that have limited resources to exploit. However, depending on their adaptation to the environment, different species have different upper limits in numerosity perception (e.g., see Davis and Pérusse, 1988). Regardless of this upper limit, a comparative analysis of numerosity perception across species shows that perception of numerosity per se, either of elements simultaneously present or one after another, is not unique to human beings. This makes it all the more likely that the development of numerosity perception is not a cognitive one, but is one that is based on processes found in other species, such as exploratory activities based on unity information. However, it is not clear whether animals also perceive the addition of a new element to a collection of elements, and whether they perceive addition on the basis of information about the persistency of unitary objects.

Numerosity perception is limited in the size of collections that one can exactly determine numerosity of. Across development, verbal counting appears to extend that function. It has often been proposed that numerosity perception serves as a developmental basis for subsequent counting abilities (e.g., see Trick & Pylyshyn, 1996). We also assume a developmental relation between numerosity perception and verbal counting that consists of shared processes in the ability of children to keep track of the elements that are explored for unity information. Basically, we view verbal counting as an extension of numerosity perception. We need more evidence on online processes that take place during numerosity perception to be able to fully test our hypothesis. By using the method of familiarization of amount of looking time, we were able to determine whether infants can perceive numerosity perception at a certain age. But this method did not give us direct insight in the processes of numerosity perception online and its development. The evidence for the development of numerosity perception is, therefore, somewhat indirect, but, nevertheless, clear.

To sum up, infants can perceive numerosity of small collections of elements. Infant's numerosity perception involves exploration processes of unity information over time and space and numerosity emerges as a result of the way these processes evolve over time within the constraints that are provided by the displays.

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Summary

In the present thesis, we addressed the basic question whether infants can visually perceive numerosity of a collection of objects and how they do this. Numerosity was defined as an invariant property of a collection of objects specifying its numerical size. Approaches to numerosity perception in infancy have generally conceived the nature of this ability and its development in terms of cognitive processes. For example, numerosity perception has been conceived as the result of processes based on non-verbal counting principles, or rudimentary arithmetic computing processes. We, however, hypothesized that the processes in detection of numerosity are perceptual and guided by information that infants obtain when they visually explore objects over time. On the basis of information about object unity and its persistence infants may perceive the numerosity of a collection of objects and anticipate the outcome of changes in numerosity. The unity of objects has to be detected, but, in addition, the quantity of objects must also be apprehended. We hypothesized that infants detect numerosity by the way their perceptual activities search for units and keep track of the units that are available over time and space. In that case, the activities may be affected by the number of elements and, thus, become differently organized when different numerosities are explored. The organization of the activities would then specify the numerosity that has been explored.

We conducted a series of four separate studies. Two studies investigated whether infants perceive numerosity of a collection of objects that are all simultaneously present. All objects undergo motions that change their patterns but leave numerosity that infants are able to keep track of constant. Another series of two studies investigated whether infants perceive numerosity of a collection of objects that changes in numerosity over time because of addition of a new object.

In the first study, we investigated whether perception of unity of objects, rather than characteristic patterns across objects, underlies numerosity perception. Infants looked at small collections of continuously moving figures (1-4) that were displayed on a tv screen. Due to motion of the figures and their continuing changing positions relative to one another, we were able to show that only discrimination of units underlies numerosity perception in infancy and not characteristic static patterns, such as a triangular configuration for three figures, that are confounded with numerosity. We used an infant-controlled habituation of looking-time task. At each of the ages 5, 8, and 13 months infants were tested for the numerosities 2, 3, and 4 in three randomly ordered sessions. The results demonstrated that infants from the age of at least 5 months on perceive small numerosities. We interpreted these results as support for the hypothesis that numerosity perception is based on unity perception.

Perception of units and their numerosity was conceived of as a perceptual process of picking up invariant information that specifies distinct units and their number

In the second study, we investigated the information that enables infants to perceive numerosity for a collection of distinct units Similarity of shape has been proposed as a source of information In that case, categorization of shape would be at the basis of numerosity perception Numerosity perception would, thus, require homogeneously shaped objects In contrast, we assumed that numerosity perception involves search processes that accumulate distinct objects on the basis of their unity information These search processes so not require that objects have homogeneous shapes Whereas the categorization hypothesis would predicted that similarity of shape would provide a basis for numerosity perception in infancy, we expected that this would not occur We investigated infants' visual perception of numerosity of small collections of independently moving, heterogeneous figures that differed in size and shape Two groups of infants, of 5 months old and 13 months old, respectively, were tested for the numerosities 2, 3, and 4 in three randomly ordered sessions The results demonstrated that numerosity was perceived for both age groups In addition, there was an effect of heterogeneity of shape that was tied to numerosity 2 Infants of 5-months-old perceived numerosity 2 for collections of two homogeneous figures but not for collections of two heterogeneous figures Although 5-month-old infants did not perceive the numerosity of collections of two heterogeneous figures, they did for collections of three figures In our view, this result might be explained by how search for unity information across elements is interfered by exploration of the shapes of elements Shape exploration appears easier for two objects than for three, especially when trajectories of the figures change and occlusions occur Thirteen-month-old infants discriminated all numerosities that were presented Apparently, numerosity perception gets more task oriented with increasing age and less easily side-tracked by exploration of individual objects

The findings of our first two studies are important They are the first in the area of numerosity perception to use elements in motion Until these studies were carried out, displays always consisted of stationary objects Our studies replicated previous findings that infants as young as 5-months-old can perceive small numerosities (1-4) of static objects By introducing motion to displays of elements, our studies extended previous knowledge of what numerosity perception in infancy may involve As we have argued, our findings provide evidence that numerosity is perceived through exploratory activities on elements that are bounded and have unity (i e , objects) Our findings are not so easy explained by various accounts that propose cognitive processes as the basis for numerosity perception. Also our findings extended the insights on how numerosity perception in infancy may develop. Specifically in early development, numerosity perception is affected by the spatiotemporal properties that constitute the context of elements.

Numerosity not always remains constant, but may also change, for example, through transformations such as addition of an object to another object (i.e., 1+1). Displays that involve a change in numerosity over time, such as addition, provide us with a further opportunity to investigate at what age infants keep track of numerosity over time and how they do this. We investigated perception of addition in the next two studies.

First, we specifically investigated in the third study whether infants keep track of the numerosity of a collection of objects that increases through addition of another object. Addition was displayed as a figure that came into view from the side of a TV screen and was added to figure(s) already present. For an addition event (e.g., 1+1), the numerosities over time are the initial or augend collection (i.e., 1), the addend or the numerosity of objects that are added (i.e., 1), and, finally, the sum or the collection of objects that results after the addition (i.e., 2). The results showed that infants start discriminating numerosities in an addition somewhere between 8 and 14 months of age. But even at 14 months of age, not all numerosities during addition were discriminated. At this age, infants perceived that no addend as well as a larger addend than the old addend (+1) occurred. Infants still did not perceive that an addition occurred with a smaller augend collection. Previous studies had shown that infants can perceive numerosity from 5 months old, but this study, nevertheless, showed that infants do not perceive numerosity when, soon after presentation, it is changed through addition.

The results on perception of addition were inconsistent with the view that infants anticipate the outcome of an addition by computing this outcome from the numerosities of the initial augend and the addend that compose an addition. At 5 months of age, infants did not discriminate any component of an addition event, whereas anticipation of the outcome of addition has been demonstrated at this age. The findings were discussed in relation to infants' exploratory activities over time. We also discussed the problems infants may have with keeping track of parts of this event.

Because the findings on perception of components of addition suggested that the outcome of addition is not computed from augend and addend, we further investigated perception of addition. We conducted a fourth study that was comparable to previously reported studies of perception of the outcome of a addition. We investigated whether 8- and 14 month-old infants anticipated the outcome of a simple addition. The addition that we presented involved one object that was placed into sight and, subsequently, concealed by a container. A second object was, then, shown and put into the container (i.e., 1+1). Only 14 month-old but not

8-month-old infants anticipated that the outcome of this addition would be two, and not one or three objects. These results deviated from results of other studies on addition (1+1) that suggested that perception of the outcome was already present at 8 months. To explain this deviation, we suggested that perception of the unity and persistence of objects within a container might be problematic for younger infants, because the space occupied by the container includes the space occupied by the objects in the container. Perhaps occupation of separate spaces is necessary for infants' perception of the unity and persistence of objects.

We discussed our overall findings and their implications with reference to our perceptual view of numerosity perception and current counting models. We argued that the variability of the outcome of infants' exploration processes cannot easily be explained by counting models. We concluded that our findings might be more easily reconciled with a perceptual model of numerosity perception that involves exploration processes of unity information over time and space. As a consequence, numerosity would emerge by the way these processes evolve over time within the constraints that are provided by the displays.

Samenvatting

In dit proefschrift onderzochten we de vraag of baby's het aantal van een verzameling objecten visueel konden waarnemen en hoe ze dat deden. Aantal hebben we omschreven als een invariante eigenschap van een verzameling objecten die hun numerieke grootte specificeerde. In het algemeen hebben benaderingen van aantalwaarneming in baby's de aard van deze vaardigheid en zijn ontwikkeling beschouwd in termen van cognitieve processen. Aantalwaarneming is bijvoorbeeld opgevat als het resultaat van processen die gebaseerd zijn op nonverbale telprincipes of lijken op latere rekenprocessen. In plaats daarvan veronderstelden wij dat de processen van aantalwaarneming perceptueel zijn. Ze worden gestuurd door informatie die baby's verwerven wanneer zij objecten in de tijd exploreren. Op grond van informatie over de eenheid en persistentie van objecten zouden baby's het aantal van een collectie objecten waarnemen en de uitkomst van veranderingen in het aantal anticiperen. Behalve de eenheid van objecten moet ook nog hun aantal vastgesteld worden. Wij veronderstelden dat baby's aantal waarnemen door de manier waarop hun perceptuele activiteiten zoeken naar eenheden en de eenheden bijhouden die beschikbaar zijn over tijd en ruimte. In dat geval kunnen die activiteiten beinvloed worden door het aantal elementen, en dus verschillend verlopen als verschillende aantallen geëxploreerd worden. De organisatie van deze activiteiten zou dan specificeren het aantal dat geëxploreerd is.

We ondernamen een serie van 4 studies. Twee studies hielden zich bezig met de vraag of baby's het aantal van een verzameling objecten waarnemen wanneer alle objecten tegelijk aanwezig zijn en ononderbroken bewegen. Door de beweging veranderen de patronen voortdurend, maar blijft het aantal dat baby's kunnen waarnemen constant. Twee andere studies hielden zich bezig met de vraag of kinderen het aantal waarnemen van een verzameling objecten dat na verloop van tijd verandert van aantal door toevoeging van een nieuw object.

In de eerste studie onderzochten we of waarneming van eenheid van objecten in plaats van waarneming van karakteristieke patronen van objecten ten grondslag ligt aan aantalwaarneming. Baby's keken naar kleine verzamelingen van voortdurend bewegende figuren (1-4) die werden vertoond op een tv-scherm. Door de beweging van de figuren en hun voortdurende veranderende positie ten opzichte van elkaar, waren we in staat aan te tonen dat discriminatie van eenheden in plaats van karakteristieke, statische patronen die zouden samengaan met een bepaald aantal, zoals een driehoek voor drie figuren, ten grondslag ligt aan aantalwaarneming in de baby-tijd. We gebruikten een habituatie van kijktijden-taak. Op de leeftijden van vijf, acht en dertien maanden werden de baby's steeds getest op de aantallen 2, 3, en 4 in drie willekeurig

geordende sessies De resultaten toonden aan dat kinderen vanaf de leeftijd van tenminste 5 maanden kleine aantallen waarnemen We hebben deze resultaten opgevat als een ondersteuning van de veronderstelling dat discriminatie van eenheden ten grondslag ligt aan aantalwaarneming in plaats van karakteristieke patronen. Discriminatie van eenheden en hun aantal werd opgevat als een perceptueel proces waarbij invariante informatie werd opgepikt die afzonderlijke eenheden en hun aantal specificeert

In de tweede studie onderzochten we de informatie die kinderen in staat stelt het aantal waar te nemen van een verzameling afzonderlijke eenheden Gelijkheid van vorm is ooit voorgesteld als bron van die informatie In dat geval zou categorisatie van vorm aan de basis liggen van aantalwaarneming Objecten met een homogene vorm zouden daarom vereist zijn voor aantalwaarneming Daartegenover veronderstelden wij dat gelijkheid van vorm niet noodzakelijk was omdat de zoekprocessen in aantalwaarneming alleen maar op het onderscheiden van eenheden zijn gebaseerd Onze hypothese was dus dat gelijkheid van vorm geen basis was voor aantalwaarneming bij baby's We onderzochten de visuele waarneming door baby's van aantal voor kleine verzamelingen van onafhankelijk bewegende, heterogene figuren die verschillen in grootte en vorm Twee groepen baby's een van 5 maanden oud en een van 13 maanden oud, en werden getest op de aantallen 2, 3 en 4 in drie willekeurig geordende sessies De resultaten toonden aan dat aantal werd waargenomen door beide leeftijdsgroepen Daarnaast was er een effect van heterogeniteit van vorm die beperkt was tot het aantal 2 Baby's van 5 maanden oud namen het aantal van 2 voor homogene figuurtjes waar maar niet voor heterogene figuurtjes Aangezien baby's de andere aantallen wel waarnamen, kon ons inziens het resultaat verklaard worden met de manier waarop het zoeken naar informatie over eenheden verstoord wordt door exploratie van de vorm van elementen Vorm-exploratie is gemakkelijker voor twee objecten dan voor drie, speciaal wanneer de voortgang van objecten verandert en occlusies gebeuren Dertien maanden oude baby's discrimineerden alle aantallen die hun werden getoond Blijkbaar wordt aantalwaarneming meer taak georienteerd met toenemende leeftijd en minder gemakkelijk verstoord door eploratie van individuele elementen

De bevindingen van onze eerste twee studies zijn belangrijk Ze zijn de eerste op het gebied van aantalwaarneming die bewegende elementen gebruikten Totdat onze onderzoekingen uitgevoerd werden bestonden displays altijd uit statische elementen Wij repliceerden eerder bevindingen dat baby's van ten minste 5 maanden oud kleine aantallen (1-4) van statische elementen kunnen waarnemen Door beweging aan displays van elementen toe te voegen breidden we onze kennis uit over wat aantalwaarneming in baby's inhoudt We hebben uiteengezet dat deze bevindingen steun gaven aan onze veronderstelling dat aantal wordt waargenomen door exploratieve activiteiten gericht op elementen die begrensd zijn en eenheid hebben (ofwel objecten). Onze bevindingen worden niet zo snel verklaard door verschillende verklaringen van aantalwaarneming in termen van cognitieve processen. We hebben ook aangevoerd dat onze bevindingen het inzicht vergrootten op hoe aantalwaarneming in de baby-tijd zich zou ontwikkelen Met name vroeg in de ontwikkeling wordt aantalwaarneming beinvloed door spatiotemporele eigenschappen die de context bepalen van elementen.

Aantallen blijven niet altijd constant maar kunnen ook veranderen, bijvoorbeeld, door transformaties zoals toevoeging van een object aan een ander object (i.e., 1+1). Displays die een veranderingen van aantal inhouden, zoals door toevoeging, gaven ons een nieuwe kans te onderzoeken op welke leeftijd baby's een aantal volgen in de tijd en hoe We onderzochten waarneming van additie in de volgende twee studies.

Eerst onderzochten we in de derde studie of baby's het aantal van een verzameling figuren volgen dat toeneemt door toevoeging van een ander object. Additie werd vertoond als een figuur dat in beeld kwam vanaf de zijkant van een tv-scherm en werd toegevoegd aan de figuren die al in beeld waren. In het geval van een toevoeging (b.v., 1+1) zijn de aantallen die achtereenvolgens voorkomen de augend verzameling (i.e., 1), de addend of het aantal elementen dat wordt toegevoegd (i.e., +1), en tenslotte de som of uiteindelijke verzameling elementen die overblijft na de toevoeging (i.e., 2). De resultaten tonen aan dat baby's aantallen binnen een additie gebeurtenis die toevoeging inhoudt, beginnen te onderscheiden ongeveer tussen 8 en 14 maanden. Maar zelfs op 14 maanden worden niet alle aantallen gedurende een additie onderscheiden. Op deze leeftijd namen baby's waar dat er geen addend en een grotere addend dan de oorspronkelijke addend (+1) voorkwamen. Baby's namen toen nog steeds niet waar dat er een additie gebeurde met een kleinere augend aantal dan eerder vertoond. Eerdere studies hadden aangetoond dat baby's aantal kunnen waarnemen vanaf 5 maanden, maar onze studie toonde aan dat baby's aantal niet waarnemen wanneer kort na vertoning het aantal verandert door een toevoeging.

De resultaten over de waarneming van additie waren strijdig met het opvatting dat baby's de uitkomst van een additie anticiperen door de uitkomst te berekenen op grond van de aantallen van de augend en de addend die deel uitmaken van een toevoeging. Op 5 maanden onderscheidden baby's nog geen enkele component van een additiegebeurtenis terwijl anticipatie van de uitkomst van additie op deze leeftijd wel is aangetoond. De resultaten werden besproken in samenhang met de exploratieve activiteiten van baby's Ook werden de problemen besproken die baby's kunnnen hebben met het volgen van onderdelen van een additiegebeurtenis.

We onderzochten waarneming van additie nog verder omdat de resultaten van de waarneming van additie-componenten suggereerden dat de uitkomst van additie niet berekend wordt uit augend en addend. We ondernamen een vierde studie die vergelijkbaar was met al gerapporteerde studies over de waarneming van de uitkomst van additie. Wij onderzochten of 8 en 14 maanden oude baby's de uitkomst anticiperen van een eenvoudige additie (1+1). De additie die wij presenteerden hield in dat een object dat in het zicht van de baby stond vervolgens werd verborgen in een container. Een tweede object werd vervolgens getoond en dan in de container gestopt (1+1). Alleen veertien maar niet 8 maanden oude kinderen anticipeerden dat de uitkomst van deze additie 2 en niet 1 of 3 objecten zou zijn. Deze resultaten weken af van de resultaten van andere studies over de additie (1+1) die suggereerden dat waarneming van de uitkomst al aanwezig was op 8 maanden. Om deze afwijking te verklaren, stelden we voor dat waarneming van eenheid en persistentie van objecten in een container problematisch zou kunnen zijn voor jongere baby's omdat de ruimte die wordt ingenomern door een container ook de ruimte omvat die wordt ingenomen door de objecten in de container. Mischien is vroeg in de ontwikkeling de inname van verschillende ruimten noodzakelijk voor de waarneming van eenheid en persistentie van objecten.

We bespraken al onze bevindingen en hun implicaties voor ons perceptuele model en bestaande telmodellen voor aantalwaarneming in baby's. We beredeneerden dat de variabiliteit van de uitkomst van de exploratieprocessen in baby's niet gemakkelijk verklaard kan worden door telmodellen. We concludeerden daarom dat onze bevindingen gemakkelijker pasten binnen een perceptueel model van aantalwaarneming dat exploratie-processen van eenheid en persistentie inhoudt die verlopen over tijd en ruimte. Aantal zou dan tot stand komen door de manier waarop deze processen ontstaan en verlopen binnen de beperkingen van het display en in de tijd dat baby's verzamelingen objecten kijken.

Curriculum Vitae

Erik van Loosbroek werd geboren op 1 juni 1956 te Schiedam. In 1975 behaalde hij het diploma Gynmasium ß aan het Gymnasium Ypelaar te Breda. Na 14 maanden dienstplicht vervuld te hebben bij het korps Koninklijke Marechaussee begon hij in 1976 met een studie psychologie aan de Katholieke Universiteit Nijmegen. Na zijn kandidaats koos hij als hoofdrichting ontwikkelingspsychologie en als specialisatie funktieleer. In 1983 studeerde hij af op een onderzoek naar de ontwikkeling van klasse-inclusie bij kinderen. Tijdens zijn studie verbleef hij korte tijd aan het Institute of Child Development te Minneapolis in de Verenigde Staten waar hij ervaring opdeed met methoden van baby-onderzoek. Van 1983 tot 1987 werkte hij als wetenschappelijk onderzoeker voor het NWO aan het onderzoeksproject waarvan in deze dissertatie verslag wordt gedaan. In 1989 begon hij met de lerarenopleiding 1ste graads economie aan de Katholieke Universiteit Nijmegen en de Katholieke Universiteit Brabant die hij in 1994 afrondde. Vanaf 1992 tot 1995 was hij steeds tijdelijk werkzaam als leraar economie op verschillende middelbare scholen in 's-Hertogenbosch, Nijmegen, Cuyk en Breda. Sinds 1994 is hij als freelance docent werkzaam voor de Leidse Onderwijs Instellingen. In 1995 werkte hij als wetenschappelijk onderzoeker bij de vakgroep ontwikkelingspsychologie aan de Katholieke Universiteit Nijmegen. Aan deze vakgroep is hij sinds 1996 verbonden als docent en verzorgt onderwijs in de cognitieve en perceptuele ontwikkeling. Vanaf 1995 is hij ook verbonden aan het Max Planck Instituut voor Psycholinguistiek te Nijmegen waar hij onderzoek doet in het kader van het Scope-project.